Volume 18 Number 1

BULLETIN
of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

JANUARY 1934

Symposium on Geophysics

FOREWORD

At the present time there are more than fifty reflection seismograph parties operating throughout the United States. The vast majority of this work is in Oklahoma and Texas. There is considerable gravimetric work being carried on, mainly in the Gulf Coast. While the magnetometer has lost ground compared with a few years ago, there are still a few parties in the field.

The total monthly outlay on reflection seismic operations must be more than a half million dollars, with every expectation that this expenditure will increase as the known reserves of oil decrease, and as the oil business becomes more profitable. The increased confidence in reflection seismic methods, both dip and correlation, will also contribute to this expanding program. In spite of several failures, some due to carelessness and others to lack of understanding of the limitations of the method, there are still some notable recent successes. The manner in which well spacing and townsite drilling was discussed at Tomball prior to the first well being spudded shows how great was the confidence of the oil fraternity in the work in this new area.

With the realization that this method was becoming successful and that the pioneer work was done, and with the desire to get their share of the juicy half million dollar plum, several consulting companies have been organized. Under competitive bidding, prices have been reduced to the point where there is barely an adequate return on the investment and certainly no money for research and development.

In a further effort to keep the program costs as low as possible, inadequate data have been frequently obtained, so that, even in the hands of a skilled seismologist, there has been insufficient material for a proper analysis. Small wonder then that he has made mistakes.

The foregoing statements are not so true of the magnetic and gravimetric work. Since the stations are in both cases appreciably cheaper than seismograph datums, it was easier to persuade the users of these methods to increase the density of observations.

If advances in the art are to be made by the consulting companies, they must have not only sufficient profits to invest in experimental work, but also capable personnel willing to carry on experimentation. Much work of the type reported on in this issue must be done so that in the future geophysics will be charged with fewer failures and more successes.

B. B. WEATHERBY

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 3-12

RELATIONS OF GEOPHYSICS TO GEOLOGY[1]

PAUL WEAVER[2]
Houston, Texas

ABSTRACT

The present aim of geophysical methods is to construct subsurface contour maps. Three principal methods, viz., measurement of gravity, of magnetic field, and of electric field, are forms of measurement of a potential function, and consequently have inherent limitations for construction of contour maps.

Another principal geophysical method is the seismic, which does not measure a potential function, and is inherently suitable for constructing contour maps.

Both types of methods have difficulties in constructing contours due to variations in physical character of rocks. Suggestions are made for coöperation of geology and geophysics to minimize these difficulties.

If we study current scientific literature, we observe that new phenomena are being discovered in all branches of physics by precise measurements aided by mathematical analyses, and that the tools and technique for applying these discoveries to commercial processes are being evolved at the greatest speed in history. Geophysics has kept pace in this general development of physics and attempts are being made to increase its applications to commercial processes in all directions. It is the purpose of this discussion to survey the commercial application of geophysics to the oil development problems and especially its relation to the similarly expanding efforts in geology.

In this rapid development of science, it is always necessary to examine critically each new process to be sure that it has a place in commercial work. Some of our advances are not yet necessary for the present state of commercial operation. We may illustrate in the following manner.

More than nine-tenths of the people in the world to-day probably think that the sun rises every morning in the east and sets every evening in the west. This interpretation of what they see is sufficient for their actions, and they need no other in their daily chores unless they be seafaring people who steer their own boat; in such a case they can determine their position at sea best by studying astronomy and learning that the earth moves, not the sun. Similarly, the average man in oil (including the geologist) will not learn the later developments in

[1] Read before the Association at the Houston meeting, March 24, 1933. Manuscript received, November 4, 1933. Presidential address, Society of Petroleum Geophysicists.

[2] Gulf Production Company.

physics, including geophysics, unless he needs them to solve a geological or a mechanical problem not readily understood by his former teaching and its interpretation of his former experience.

Geophysics, like geology and like chemistry, began with the finding of novelties. For example, the first chemists mixed together various combinations of substances and observed that, although usually the substances preserved their identity, and could subsequently be separated, in some cases, substances were changed by juxtaposition, and lost their identity, so that new names were necessary for the resultant new substances. Chemistry of twenty-five years ago was principally a memorizing of names of the substances which were formed by the juxtaposition, technically called a "reaction," of other substances. Now, however, chemistry not only foretells the products of a reaction, under different environments, but calculates numerically the rate at which the reaction is carried out and the heat evolved during the process.

In geology, both applied to mining and to oil, pioneers were looking for novel structures, such as anticlines and faults, which they had found to be present where known commercial deposits existed. Now, however, a change similar to that of chemistry has come in geology. In geology we now talk about the amount of closure on the surface beds of an anticline, the number of feet of throw and of hade of a fault.

Our latest development in geophysics has been an endeavor to give profiles and contour maps to the anomalies which we discover. Now this advance in geophysics requires very accurate measurements, which means a very careful calibration of the measuring device, especially in view of the fact that these measurements are carried on in the field and can not be exempt from the effects of variations in temperature and in other factors of operating environment.

Although further improvements are constantly being made, the instruments now available for geophysical measurements in most cases already have the precision necessary for the present state of the art.

It is also generally agreed that the technique of operation is advancing equally with the instrumental precision and is already being handled satisfactorily by the experienced operators.

The present high specialization in instruments and technique is gratifying, but does not insure that geophysics can successfully solve all the problems which it is now attempting. We must find out whether the problems are theoretically capable of solution, and I must assume in the discussion which follows, on the part of the geologists, a certain

knowledge of mathematical theory, but I shall try to present analogies which will make the discussion nonmathematical as far as applications are concerned.

A geophysicist may be likened to a civil engineer who accompanies an explorer around the world. If the two are in a big city, such as New York, where there are many high buildings close together, the explorer may ask the engineer to calculate the height and capacity of a building on a crooked street where there is heavy traffic and where the building is sandwiched between others. Data for such calculations may comprise not only measurements along the street, but also measurements from some window of adjoining buildings, and the latter may be necessary for accurate results.

Now suppose the two pass across the country to the Colorado Rockies and the problem is to construct an aerial tramway from a mine. At the mine high on the mountain side, the engineer looks across a canyon to a sharp rock pinnacle which he can not occupy himself, and he wishes to determine the span from the mine to the pinnacle.

The explorer and the engineer continue westward in a car and cross the mountains to the edge of Death Valley. They have no map and the explorer wishes the engineer to determine the shortest distance across the Valley to a water hole.

These three problems are similar to problems which the geologists present to the geophysicists. The first problem is one where measurements can be taken a relatively short distance from the object to be measured, and where any point at which measurement is desired is accessible. There is some difficulty in determining vertical angles and in using the stadia on account of the crowded streets, but the problem can be worked out to any degree of accuracy.

The second problem is one where measurements are somewhat restricted, namely, to a certain position, but where clear atmosphere gives very great precision to such measurements as are made, and enables the engineer, with an accurate transit, to measure distance from a very short base line.

The third problem is the difficult one. As the engineer stands on the edge of the desert valley, instead of clear view to the opposite hills, he sees a mirage. If he is so fortunate as to obtain a vantage point from which part of the opposite range is clearly visible, he is too far to identify vegetation which might be characteristic of a water hole. In most cases, the best he can do is to indicate the nearest point of the mountains on the opposite side of the valley and can tell nothing as to whether they contain at that point the water which is necessary to the traveler. The desert interferes with accurate measurements

of the distance across the valley, variations in temperatures and density of the air give rise to refraction, dust clouds decrease visibility, the party must continue because they have a limited time within which they must obtain water, and extended surveys are therefore not permitted. The engineer, however, must make some recommendation, as the party must go on, and this is the situation which is generally present in our geophysical problems of to-day.

The first successful geophysical application to commercial work was the determination of depth to the ocean bottom, and this problem is analogous to the measurement in the Colorado mountain because the water between the measuring device and the object whose position is sought by the measurements has only slight variation in physical properties, and a calibration chart for these variations can be readily made. There are some geophysical problems where these conditions also exist, but they are not the ones to which our greatest effort is being devoted at this time.

The principal geophysical methods which are being used are familiar to all of you. The measurements made by these methods are of the variation of gravity, of the variation of magnetic field strength, of the variation of electrical field strength, and of the variation in velocity of sound. They have been divided into methods which represent the measurement of a natural field and those which give the measurements of an artificial field, but in considering the relation of geophysics to geology, a different classification is necessary, and the geophysical methods may be divided into two classes, those which measure a potential function or some of its components, and those which determine a point.[3]

[3] The reader is referred for a complete discussion of a potential function to: W. D. MacMillan, *The Theory of the Potential* (McGraw-Hill Book Company, 1930). For the aid of those who are not at present interested further than in this present article, the following short summary may serve:

Bodies in space exert force upon other bodies at a distance. The amount of the force varies in some way with the distance, usually inversely as the square of the distance. Some kinds of force are attractive, some repellent. Now to define the potential, let us take one body, which we call A, at a fixed position. Let us move another body from a point 1 in space to a point 2, and let this second body be so small that every part of it can be considered the same distance from A, so we will call it P, meaning a particle. It will require work to move it from 1 to 2 if they are at different distances from A. Then, the amount of this work is equal to the difference in the values of the potential function for 1 and for 2.

The potential function is a number, since work is a number. It has no direction, but it changes in general from every point in space to the next one, and at different rates. We express this by saying that the potential function is a scalar function of position, and that its derivatives are the components of a vector.

Gravity, magnetic, and electric forces each vary inversely as the square of the distance, but differ in that the gravity force is always one of attraction, whereas the magnetic and electric may be either attractive or repellent. The potentials for these forces, therefore, "differ from one another only in the constant factor of proportionality

Gravity, magnetic, and electric geophysical methods are measurements of a potential function, but the seismic method is not. From the standpoint of geology and geophysics, measurements of the potential function and its components have the following implications.

1. Size (that is, mass) and distance cause most of the effect. The larger the mass, the greater the effect. The greater the distance, the less the effect.

2. All bodies have an effect, and this effect can become very small only if the body is very small, or very far away.

3. The shape of the body modifies the effect only slightly.

In reconnaissance geology, we wish to find the existence of large bodies, and so potential function methods are valuable in reconnaissance. In detail geology, we wish to construct a contour map of a comparatively small segment of a surface of a body, and therefore unless we can determine the shape of this segment very accurately, we can not construct accurate maps; thus, in this case the potential function methods are not easy to apply unless the part of the body which we wish to contour is very close to our observation point as compared with the rest of the body.

The seismic method is not a potential function method and it attempts to map contours on an underground bed, or beds, by determining surfaces which are the possible loci of the travel of a sound wave, the bed sought being the envelope of these loci. The seismic method is intended, therefore, to give a result which determines uniquely the depth to a bed, or beds, below the point of observation, and is probably the only method which gives theoretical possibilities of being the equivalent of core drilling; it has theoretical possibilities for constructing contour maps greater than those of core drilling, because the seismic method in order to determine the depth below a point of observation determines the amount and direction of slope at that point.

The statements made in the preceding paragraph are general, and, like all generalities, are wrong. In certain cases, measurements of the potential function can be used by the geologists for contouring because the number of possible distributions of matter which might give the measurements are limited by known facts regarding the geology. For example, a very strong gravitational minimum covering a limited area where sedimentary rocks are present to considerable depth must be caused by salt or by a large block of diatomaceous shale. There-

---

which is associated with the potential; this factor of proportionality depending upon the forces under consideration and the system of units which is employed" (MacMillan, *op. cit.*, p. 283).

fore, the geologist can restrict the interpretation of such a sharp gravity minimum to a relatively simple picture of a salt dome, or an anticline, depending on the shape and sharpness of the minimum. Again, although the seismic method is supposed to give a unique solution, unknown variations in the formation traversed by the sound wave may give several alternative interpretations.

At the present time we are asking that the geophysical report for a salt dome shall include an estimate of the depth to the salt, the area of its cross section, and the existence of an overhang on some part of the periphery. When these additional questions are asked, the difficulty of obtaining the information by potential function methods becomes very great. We do not refer to the practical difficulty of making very accurate measurements, but to the theoretical difficulty, or what we shall call the resolving powers of the method. To refer to our desert analogy, as we look across the valley to the hills on the far side, we can appreciate that these hills have certain salients and alluvial fans, but we can not, even with a powerful telescope, see the minor topographic details because the air through which the light travels prevents obtaining a proper stereoscopic picture. We can see the same difficulty if we go up in an airplane on a day when there are no shadows. At slight elevations we can estimate visually the height of buildings, but at 10,000 feet, we can calculate the height of buildings only by photographs taken several hundred feet apart, and can do this accurately only when the photograph is very clear and there are no local hazy spots in the air between us and the ground.

The potential function methods, therefore, will always have a limit when we try to make profiles and contour maps of the top surface of buried structures because the resolving power of these methods is inadequate. Even where the structures which are being studied are shallow, this difficulty appears. For example, a single bed which is thin and a very good conductor can be mapped by electrical methods, but where there are three good conductors at fairly short intervals, even if all of them are shallow, the electrical problem becomes extremely difficult. Now the limit in resolving power of the potential function methods applies not only where there are a number of beds which we are trying to map, as in the electrical case just mentioned, but it applies also to the kind of surface which a single bed may have. For example, to distinguish between a fault and a short steep dip becomes an impossible problem in certain measurements.

There is a further difficulty in geophysical surveying by potential function methods. It is necessary to extend the surveys to a considerable distance because the rate of change of the values measured is im-

portant for the interpretation. In areas where there are a number of anomalies close together, it therefore results that the effect of each anomaly is obscured by effects from adjacent ones.

Potential function measurements can be made of numerical value where there is a large effect of a body of a known geometrically simple form near the points at which measurements are made. The successful contouring of the top of cap rock in some of the shallow salt domes by Barton is the most brilliant example of this method.

The geologist can aid very much in the interpretation of the potential function type of geophysical survey by obtaining as much information as possible regarding the type of structure to be expected in a particular area and by regional studies to indicate to the geophysicist the most probable locality for investigation for anomalies.

By the seismic method, it is possible theoretically to make accurate determinations from a few observations close together. This method, therefore, has an advantage over the potential function methods in requiring very much less areal extent to be investigated. However, in actual field surveys, the problem is not as simple as indicated by theory. Corresponding with the bending of light waves through the air over a desert, we have the bending of sound paths underground, due to irregular distribution of elasticity and density in sedimentary rocks. These variations are in part a result of depositional conditions and as such show a general stratification parallel to the bedding; and the geophysicist should call on the geologist for aid in studying these variations of sedimentation. But, in addition to such variations, there is some evidence gradually accumulating that uplift will effect changes in the elasticity and density sufficient to require consideration in the accurate determination of depths which are now being attempted with the reflection seismograph. This is one of the most important studies which geophysicists must make before contouring can be precise, and it is one where the aid of the geologist is especially important. At the present time we are assuming, for lack of complete data, that formations arched over a structure maintain the same physical constants as when they are in a normal position.

How can the geologists and the geophysicists set about finding the variations in physical character of the rock caused by structures of the type we are studying in the oil fields? In the first place, we can use wells which have already been drilled on other structures and study variations reported by the drillers. So-called concretionary zones in shales and gumbos, and indurated sand members, may be due to the uplift of beds containing solutions into an environment of less pressure and temperature, thereby causing precipitation. Folding and

faulting may cause tension at some points, compression at others, and through long periods of time the physical constants of the rock change accordingly. We have practically no quantitative data on such changes as may occur in gentle folding and faulting although there is a considerable body of information regarding the effect of high pressures such as are found in structures in more intensely folded regions. A careful study of geophysical surveys, particularly reflection shooting and shooting in wells, from areas where the geology is known from a number of wells, and where samples are available from these wells for study of their physical characteristics, will contribute materially to the interpretation of results on new prospects. This study will also result in throwing much light on some of the tectonic questions which geologists have considered, such as the theory of elastic rebound. Correlation of geophysical results by reflection shooting in known oil fields with the geology should be the most obvious and simple test of geophysical results because this method is the only one generally used which is not a potential function method, and is therefore particularly easy to understand and to interpret from the theoretical side. It is, however, one which experience shows presents fully as many problems on the practical side as other methods, due to variations in the sedimentary rocks, but these variations are the ones where we find the geologists have already collected so much data that joint effort should give solutions to many of these practical problems.

In connection with the comparison of geophysical contour maps with geological contour maps based on a number of wells, there is a further caution necessary. Although reflection shooting is supposed to determine the slope and depth at a point, contours based on a number of such determinations are usually smoothed out and are so drawn as to give a most probable value to the contour. This is the proper procedure, if the determinations are supposed to be made on a warped surface, but if the horizon which is being contoured represents an unconformity, or a line of irregular cementation, the topography of the surface itself may be fine-textured. Unless the determinations with the seismograph on such a rough surface are made at exactly the same point at which the wells are drilled, there will be a chance for differences between the two sets of results at certain localities equal to the irregularity of the surface which is being mapped. These differences do not come about on account of the resolving power of the geophysical method, but are due to the fact that sufficient points have not been determined either from geophysical survey or from well data to give a picture of the real roughness of the surface being mapped.

For example, there are certain localities along the Dos Bocas-Alamo anticline in Mexico where the upper surface of the producing limestone shows deep, narrow cañons. These have been discovered because a very close spacing of wells happened to be made at their locality. If the wells had been spaced farther apart, the existence of such narrow cañons in the limestone would probably have been unsuspected. Similarly, the usual geophysical survey of this ridge would miss these cañons. It therefore is very important for the geologist to advise the geophysicist whether the history of an area gives any clues to the existence of very irregular formation boundaries, because such a condition may not be found by surveying unless very close spacing is used, which will not generally be the case in prospecting work.

In the foregoing discussion, an endeavor has been made to show the limitations in geophysical surveying which attempts to give contour maps of an area, and suggestions have been made for the coöperation of the geologist in reducing the amount of computation to be made by the geophysicist. It is not intended to suggest that the geologist should lead the geophysicist into a particular interpretation, but rather that he should suggest the most probable type of structure and variation in physical characteristics of the rocks on such structures so that the geophysicist can arrange his survey to give the greatest light with a minimum of expense and with the greatest probability.

In summary, with regard to geophysical methods which depend on the formulae of the potential function, profiles with numerical values or contour maps can only be made by geophysical surveying under certain favorable conditions. Although such numerical results are theoretically obtainable by the seismic method, which is not a potential function method, there are uncertainties in many localities regarding the regularity of the formations which give rise in turn to uncertainties in the contour maps made by the seismic method.

Geology and geophysics represent two aspects of scientific labor which have been well explained by J. B. Dumas:[4]

> The art of observation and that of experiment are very distinct. In the first case, the fact may either proceed from logical reasons or be mere good fortune; it is sufficient to have some penetration and the sense of truth in order to profit by it. But the art of experimentation leads from the first to the last link of the chain, without hesitation and without a blank, making successive use of reason, which suggests an alternative, and of experience, which decides on it, until, starting from a faint glimmer, the full blaze of light is reached.

[4] Letter to Louis Pasteur, quoted by R. Vallery-Radot, *The Life of Pasteur*, translation by Mrs. R. L. Devonshire (Garden City Publishing Company), p. 122.

If the difference in principle between geological and geophysical methods be that described by Dumas, we see that there follows an important difference in cost. Observation on natural phenomena is very much cheaper per acre than experiment, and the geologists' reports are therefore more readily available than the geophysicists'.

It seems that there would be greater joint progress if the distinction of Dumas could be eliminated, or at least shaded. If geology will add to its observation a portion of experimental effort, we shall probably obtain some such increase in specific discoveries as we have witnessed in the application of experimentation in geophysics. Similarly, the leisurely observation of a number of geophysical results from similar areas will increase the reasoning ability of our geophysicists. The more experienced of our geophysicists are probably more successful, now, as much because they have had opportunity for observation as because they have the greatest technical skill as experimenters.

At present, it seems we have a good chance to realize the ideal of Dumas; our hopes and the great possible rewards should reconcile us to the many tedious operations in the field and laboratory, which are yet before us in our efforts toward joint progress in geology and geophysics.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 13-38, 14 FIGS.

SOME POSSIBLE APPLICATIONS OF GEOTHERMICS TO GEOLOGY[1]

C. E. VAN ORSTRAND[2]
Washington, D. C.

ABSTRACT

The generation and dissipation of heat are important factors in earth history. The present distribution of temperature down to the level of isostatic compensation can probably be determined with more accuracy than has heretofore been obtained by making use of the observations of temperatures in tunnels or across mountain ranges.

Recent geothermal surveys show that relatively high temperatures are generally associated with faults, salt domes, sand lenses, and anticlinal structures of both large and small closure.

Radioactivity and thermal conduction through oil-bearing strata are shown to be possible sources of temperature variations. Generation of heat by the oxidation of petroleum appears to be of minor importance as a heat source. The most potent source of heat is to be found in the hot rocks immediately beneath uplifts.

Ceothermal prospecting is a possibility, but as developed at present, it is much less efficient than other methods of geophysical prospecting.

COSMOGONY

Astrophysics (1)[3] teaches that the life history of the countless millions of stars distributed throughout celestial space is dependent largely on a single phenomenon—the generation and dissipation of heat. During the period of condensation of the nebula, heat is generated, until, in the interior of the resulting star, such as our sun, matter exists chiefly in the forms of electrons and protons, which may ultimately, as the temperature continues to rise, neutralize each other, leaving in their stead an electro-magnetic wave which carries off the enormous quantity of energy released by the merging together of the positive and negative charges of electricity. Such an hypothesis seems necessary to account for the long life of the stars. None of the known radioactive transformations liberates sufficient energy to maintain the sun's heat. As the loss of mass and generation of heat proceeds, a point is ultimately reached, depending on the size of the star, where its internal energy is radiated more rapidly than it is generated. Our sun has long ago passed the point of maximum temperature and is now

[1] Published with the permission of the director, United States Geological Survey. Read before the Association at the Houston meeting, March 24, 1933. Manuscript received, August 7, 1933.

[2] Geophysicist, United States Geological Survey.

[3] This and the following references are in the Bibliography at the end of this article.

about half way down the scale of diminishing thermal energy. In the course of this process, which has required a few billions of years for its completion, the earth is supposed to have been separated from the sun and subsequently cooled to its present state.

In support of the preceding hypothesis is the fact that 61 of the 91 known chemical elements that enter into the constitution of the earth have been identified, with more or less certainty, in the sun (2). Of particular interest are the elements—helium, carbon, oxygen, nitrogen, and sulphur in the atomic state, and the compounds—the hydroxyl (*OH*); ammonia, or some other compound of nitrogen and hydrogen; a compound of carbon and nitrogen, probably cyanogen; and a compound of carbon and hydrogen (3). Further evidence in support of the hypothesis that the primitive earth was molten to the surface are the facts that it now acts as a magnet, and that the density increases, probably discontinuously, from about 2.7 at the surface to a mean value of about 5.5 for the entire earth.

According to Jeffreys (4), the loss of heat from the liquid surface of the earth must have been so rapid that radioactivity was a minor source of heat prior to the solidification of the outer shell. As the solidified state was approached, feeble convection currents carried off the radioactive heat and completed the transfer of the radioactive substances toward the surface of the earth. Evidence in substantiation of the hypothesis of an increasing radioactive content of the rocks as the surface of the earth is approached is contained in the following record (4) which gives the contents by weight of Finland granites of decreasing age.

	$Ra(\times 10^{12})$	$Th(\times 10^{-5})$	$K(\times 10^{-2})$
A	2.36	0.87	2.51
B and C	4.60	2.67	3.61
D	6.21	5.85	5.06

It has also been established that volcanic rocks contain more radium than plutonic rocks. Another reason for believing that radioactive substances are concentrated chiefly in the outer layers of the earth is the fact that if the deep layers were as radioactive as the surface layers, the rocky shell could never have solidified.

COOLING AFTER SOLIDIFICATION

By taking into account radioactivity, heat conduction, and an assumed initial temperature distribution based on the increase of the melting point per unit depth in the crust of the earth, Adams (6) and Jeffreys (7) have estimated the temperature at great depths in the crust of the earth (Table I). Their calculations show that cooling may

TABLE I

TEMPERATURES IN INTERIOR OF EARTH

Depth, Kilometers	*Jeffreys °C.*	*Adams °C.*	*Depth, Kilometers*	*Jeffreys °C.*
0	0	0	300	2,090
25	600	560	350	2,290
50	800	860	400	2,490
75	940	1,090	450	2,670
100	1,080	1,290	500	2,840
125	1,220	1,470	550	3,010
150	1,360	1,620	600	3,170
175	1,490	1,760	650	3,330
200	1,620	1,900	700	3,490
225	1,750	2,030		
250	1,870	2,160		
275	1,980	2,290		
300	2,090	2,420		

have extended to somewhat more than 600 kilometers below the level of isostatic adjustment, which, according to Bowie (8), is now considered to be at a depth of about 96 kilometers, or 60 miles. Below the level of isostatic adjustment, the surfaces of constant pressure and constant temperature are perfect ellipsoids of revolution, while above this level these surfaces become more and more irregular as the surface of the earth is approached. One of the outstanding problems of the geologist is first to locate accurately the isogeothermal surfaces and second to relate them to heat sources past and present.

Neglecting the radioactivity of the sedimentary rocks, Jeffreys (9) concludes that nearly all of the heat that escapes from the surface of the earth is generated in a granitic layer which has a thickness of about 11 kilometers. Beneath this layer is an intermediate layer which is practically free from radium. It has a thickness of 22 kilometers. The discontinuities at 11 and 33 kilometers are supposed to be in agreement with seismological data. From 33 kilometers to 2,900 kilometers, another discontinuity, there appear to be no special changes in the properties of the rocks in so far as the transmission of earthquake waves are concerned. These results, unfortunately, are subject to correction on account of the difficulty of interpreting seismological data, but they are of interest to us in showing the possibility of correlating the temperatures and densities of the rocks in the outer shell of the earth. By taking into account a wide range of phenomena, including the evidence of seismology, chemistry, geothermics, cosmogony, geology, and so on, Daly (10) places the discontinuities at 30, 40, 60, 1,200, and 2,900 kilometers.

ISOSTASY

It has been found by geodetic observations that the crust of the earth extends to a depth of about 100 kilometers, or 60 miles, below

sea-level. At this depth, the pressure is supposed to be constant, that is, the weight of each column of rock per unit area extending from the level of isostatic adjustment to the surface of the ground is constant, regardless of the height of the column. This condition implies that the density of a mountain mass is less than that of the rocks beneath the adjacent plains or beneath oceans. Two hypotheses have been proposed to explain the geodetic facts. According to Pratt, the crust of the earth is of uniform depth, the density varying inversely as the elevations of the earth's surface, while according to the Airy, or the "Roots of Mountains" theory (11), the crust of the earth is supposed to be of variable thickness, and the mountains are supposed to float in the deep-seated magma just as icebergs float in water. The magmatic

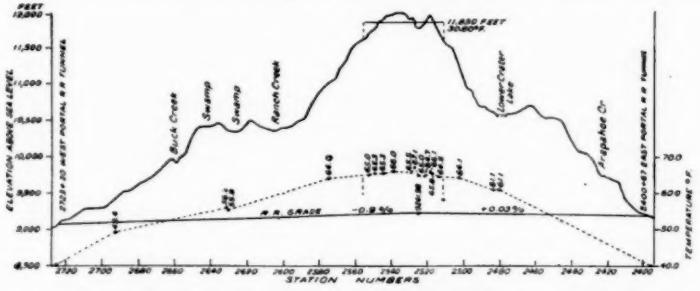


FIG. 1.—Observed temperatures in Moffat tunnel, Denver, Colorado.

rocks are supposed to be sufficiently plastic to yield to the pressure induced by the lighter strata above them and at the same time they are supposed to possess sufficient strength to carry the load imposed upon them.

Quite curiously, advocates of each hypothesis have appealed to geothermal data as a means of deciding the issue. Osmond Fisher (12) contended that the isogeotherms beneath a mountain may pass from the convex to the plane type and ultimately become concave upward. Lees (13) rejects this hypothesis. He does not believe that a mountain has solid roots extending downward into a plastic substratum and that the isogeotherms pass from the convex to the concave type.

In another publication, the writer will give a detailed application of Lees's equations to the temperature data obtained by the writer and Burgis G. Coy, resident engineer, in the Moffat tunnel. These observations are shown in Figure 1. The values, 40.0° F. at the entrances of the tunnel, and 30.80° F. at the apex of the mountain were obtained by adjusting a straight line to the observed annual mean

temperatures of the air for 41 Weather Bureau stations surrounding the tunnel. From the data included between the dotted lines in Figure 1, a reciprocal gradient (1° F. in 75.8 feet) was computed for the apex of the mountain, and then having given the profile of the mountain and the diminution of air temperature along the mountain slopes, the reciprocal gradient (1° F. in 57.6 feet) beneath the adjacent plain was determined. The results of the calculations are shown in Figure 2. The computed surface of the mountain passes through the apex of the mountain and a point on the profile which is at an elevation above

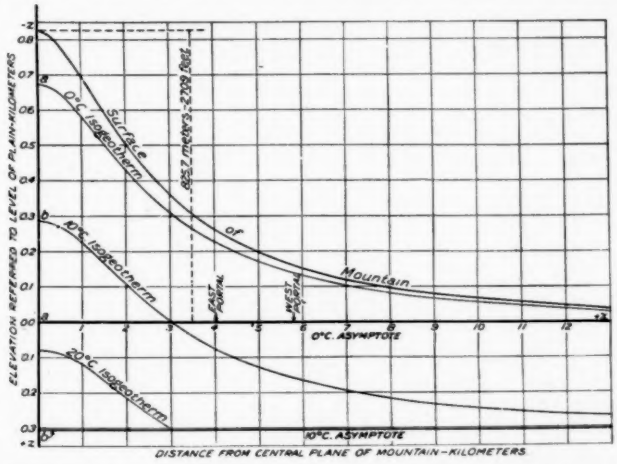


FIG. 2.—Computed profile of mountain and corresponding isogeotherms.

the plain equal to the half-height of the mountain. This approximation to the original profile of the mountain is sufficiently accurate for our purpose.

It is important to note that the profile of the mountain, the gradients at the apex of the mountain and beneath the adjacent plains, and the rate of diminution of air temperature along the mountain slope—four quantities in all—serve to fix the isogeotherms in space just as the two sides and the included angle serve to fix a plane triangle. The calculation is thus somewhat of the nature of a geothermal triangulation rather than an extrapolation to great depths. In Table II is given the rise of certain isogeotherms as they pass beneath the apex of the mountain. Thus, *a-a* in Figure 2 represents a rise of 2,207 feet. Similarly, the rise, *b-b*, is about 1,950 feet, and so on. The isotherms do not approximate to planes until a depth of 100

kilometers or more is reached. As this is the level of isostatic adjustment, it follows that the evidence supports the Pratt hypothesis. One defect has entered into the calculations. It has been assumed that the temperature gradient is constant. This gives a temperature at the depth of isostatic equilibrium which is about twice that obtained by Adams and Jeffreys as recorded in Table I. To obviate this difficulty, it can be assumed that the depth to the level of isostatic adjustment is known, and then from the equations can be determined the distribution of temperatures down to that depth which reduces the isotherms to planes at the isostatic level.

TABLE II

RISE OF ISOGEOTHERMS BENEATH APEX OF MOUNTAIN

East Portal				*West Portal*			
Tangent Plane		*Rise of Isogeothermal Plane*		*Tangent Plane*		*Rise of Isogeothermal Surface*	
Depth, Kilometers	*Temp., °C.*	*Meters*	*Feet*	*Depth, Kilometers*	*Temp., °C.*	*Meters*	*Feet*
0	0	672.5	2,207	0	0	674.4	2,213
10	316	153.4	503	10	350	126.9	416
20	632	88.2	290	20	701	71.5	235
30	949	62.0	203	30	1,051	49.9	164
40	1,265	47.8	157	40	1,401	38.3	126
50	1,581	38.9	128	50	1,752	31.1	102
60	1,897	32.8	108	60	2,102	26.1	86
70	2,213	28.4	93	70	2,453	22.6	74
80	2,530	25.0	82	80	2,803	19.8	65
90	2,846	22.3	73	90	3,153	17.7	58
100	3,162	20.2	66	100	3.504	16.0	52

POROSITY AND TEMPERATURE

Laboratory tests prove that moisture greatly increases the conductivity of soils (14). The same condition apparently holds for solid rocks (15). A comparison of the depth-temperature curve (16) with the porosity curve (17) of a deep well, Ransom No. 1, Syracuse, Hamilton County, Kansas (Fig. 3), shows that whereas the porosity decreases with the depth, the temperature gradient increases with the depth. That the latter variation may be dependent on the moisture in the rocks is readily shown by considering that the product of the thermal gradient and the thermal conductivity represents the constant flow of heat through a vertical column of unit area. As the depth-temperature curve shows that the gradients increase with the depth, it follows from the relation of constancy that the conductivity, like

the porosity, diminishes with the depth, that is, the conductivity diminishes with decreasing moisture content of the rock.

Another explanation of the curvature of the depth temperature curve shown in Figure 3 has been proposed by A. C. Lane (18). He emphasizes the fact that the upper portion of the depth-temperature curve must have risen in response to a gradual rise in the annual mean temperature of the air since the ice age. The fact, as is shown later, that the temperatures of the rocks near the surface of the ground are closely adjusted to the temperatures of the air above them, is substantial evidence in favor of Lane's hypothesis. Tests of the thermal

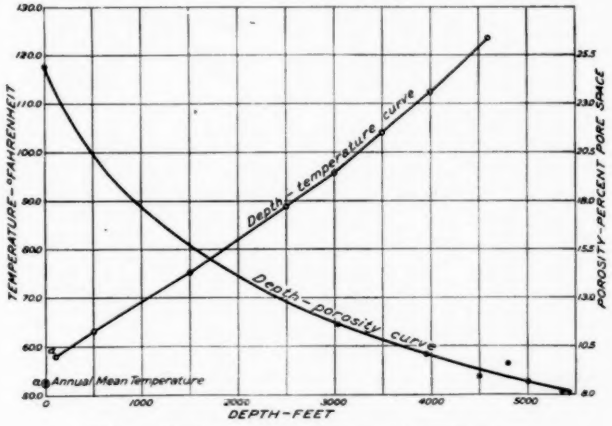


FIG. 3.—Depth-temperature curve and porosity curve.

conductivity of the rocks in their natural state at various depths in wells and mines would be of great value in the elucidation of this problem.

ERRORS IN GEOTHERMAL MEASUREMENTS

Accurate observations can be made in wells drilled with the standard rig after drilling has been discontinued for a day or two. The well must of course be free from flowing fluid at the time of the test. Wells that have been discharging fluid for a considerable time prior to the test are in unstable temperature equilibrium and the records obtained from them are not likely to be of much value.

The time required for a well drilled with a rotary outfit to reach thermal equilibrium has not been determined. It undoubtedly varies greatly with the rate of drilling, the hardness of the rocks, and many other factors. In Figure 4 are shown two curves which give some in-

formation in regard to the time required for a 2-inch diamond-drill hole to regain thermal equilibrium. The first curve represents the temperatures after drilling has been discontinued for about 30 days. The curves show clearly that the best records in a rotary hole are to be obtained a few hundred feet above the drill. This result is to be expected as the time during which the water has been in circulation is a minimum in this portion of the well.

Errors of an entirely different character appear in producing or depleted fields. Here the discharge of fluid from the producing sands

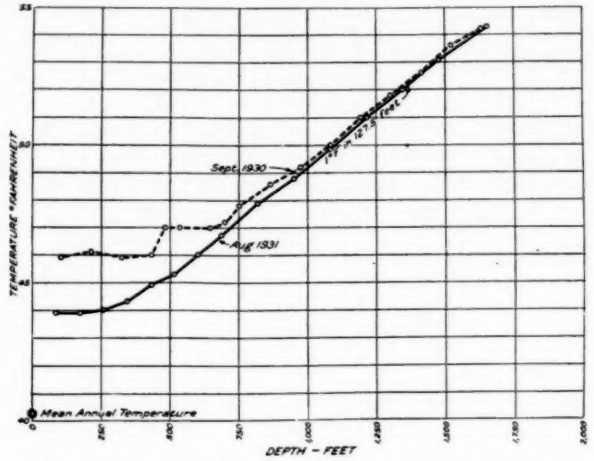


FIG. 4.—Depth-temperature curves. Diamond drill hole No. 79. Copper Range Consolidated Copper Company. Location, 1,740 feet south, 2,340 feet east, NW. corner, Sec. 1, T. 53 N., R. 35 W., Houghton County, Michigan.

tends to lower the temperatures immediately above and below the sand and to elevate those at the higher levels. Thus, wells that have been pumped rapidly for a long time, invariably show a marked rise of temperature near the surface of the ground. Furthermore, the replacement of gas and oil in the sands with water may so completely alter the thermal conductivity and heat-generating properties of the sands that the original temperatures are never restored.

RESULTS OF RECENT GEOTHERMAL SURVEYS

The American Petroleum Institute (19) has completed an extensive series of geothermal surveys extending over a period of about 5 years. More than 400 wells were tested in the states of Kansas,

Oklahoma, Texas, New Mexico, and California. The writer has made tests in 250 or more wells, some of them in each of the preceding states and some in each of the other states listed in Table III, excepting as otherwise noted in the table.

TABLE III

VALUES OF EXCESS OF SOIL TEMPERATURE OVER AIR TEMPERATURE (e) AND OF RECIPROCAL GRADIENT (1 b)

Town or Field	*County*	*No. of Wells*	e	r	r_0	$1/b$ Fl.°F.	*Range of* $1/b$	*Remarks*
Alabama								
Albany	Morgan	1	−0.5	—	—	386.2	—	12" hole; no casing
Birmingham	Jefferson	7	+2.7	0.3	0.1	96.8	8.1	
Fayette	Fayette	1	+1.7	—	—	128.3	—	
Arkansas								
Eldorado	Union	7	+0.7	1.0	0.4	49.9	3.5	
California								
Bakersfield	Kern	5	−10.1	1.6	0.8	77.0	11.0	
Coalinga	Fresno	51	−8.2	1.5	0.2	54.4	9.0	
Fullerton	Orange	1	−9.4	—	—	49.8	—	
Grass Valley (19)*	Nevada	1	+0.2	—	—	168.6	—	
Huntington Beach	Orange	4	−8.0	1.3	0.7	42.4	3.1	
Kettleman Hills	Kings	5	−10.1	3.6	1.6	55.1	9.2	
Long Beach	Los Angeles	41	−10.0	1.4	0.2	53.6	5.5	
Santa Fe Springs	Los Angeles	31	−6.5	2.0	0.4	51.6	8.1	
Seal Beach	Los Angeles	1	−1.1	—	—	33.9	—	From 100 to 3,500 ft., $1/b$ =1° in 44.3 ft.
Whittier	Orange	4	−9.9	1.3	0.7	57.6	2.2	
Colorado								
Calhan	El Paso	1	−5.9	—	—	63.5	—	
Florence	Fremont	3	−3.8	0.8	0.4	52.5	13.8	
Fort Collins	Laramie	2	−5.7	0.5	0.3	56.9	5.5	
Longmont	Boulder	1	−8.4	—	—	56.4	—	
Illinois								
Bridgeport	Lawrence	4	−1.5	0.8	0.4	58.9	7.9	
Iowa								
Ames (20)	Story	1	−2.9	—	—	143.9	—	
Kansas								
Augusta	Butler	2	−1.8	0.4	0.3	50.3	2.0	
Eldorado	Butler	24	+0.1	0.7	0.1	49.3	3.7	
Florence	Marion	4	−1.7	0.7	0.4	63.7	8.7	
Haverhill	Butler	3	−1.7	0.5	0.3	54.7	5.1	
Syracuse	Hamilton	1	−4.3	—	—	82.0	—	
Kentucky								
Prater Creek	Floyd	1	−0.8	—	—	122.0	—	
Prestonburg (near)	Martin	1	+1.4	—	—	118.4	—	
Louisiana								
Blue Lake	Sabine	2	−3.3	0.2	0.1	55.8	0.5	
Caddo Lake	Caddo	1	+1.0	—	—	37.7	—	
Caddo Lake (near)	Caddo	3	+1.8	0.5	0.3	36.9	0.9	
Haynesville	Claiborne	1	+0.2	—	—	48.2	—	
Homer	Claiborne	8	+1.0	1.1	0.4	36.1	2.5	
Many	Sabine	6	+0.1	0.5	0.2	51.7	1.7	
Pine Island	Caddo	1	+0.4	—	—	35.1	—	
Sligo	Bossier	2	+0.9	0.2	0.1	38.3	0.7	
Zwolle	Sabine	3	−2.1	1.6	0.9	53.7	4.5	
Michigan								
Surrey Township	Clare	1	0.0	—	—	84.3	—	
Houghton	Houghton	2	−1.4	0.2	0.1	128.2	2.7	
Lake Linden	Houghton	1	−4.3	—	—	160.2	—	
Mississippi								
Jackson	Rankin	1	+2.1	—	—	34.4	—	

TABLE III (*Continued*)

Town or Field	*County*	*No. of Wells*	*e*	*r*	*r_0*	*1/b Ft.·°F.*	*Range of 1/b*	*Remarks*
Montana								
Anaconda (21)	Deerlodge	1	+2.1	—	—	38.0	—	
Conrad-Kevin-Sunburst	Teton and Toole	10	−4.0	0.8	0.3	84.0	25.8	
Nevada								
Virginia City (22)	Storey	1	+1.7	—	—	29.4	—	
New Jersey								
Franklin Furnace	Sussex	1	−0.4	—	—	276.1	—	
New Mexico								
Artesia	Eddy	4	−5.4	1.2	0.6	173.9	—	
Carlsbad	Eddy	1	−3.9	—	—	147.1	—	
Lovington	Lea	1	−1.7	—	—	79.9	—	Omitted on map, probably incorrect
Roswell	Chaves	2	−6.4	0.4	0.3	188.3		
North Dakota								
Lonetree	Ward	1	−6.1	—	—	63.4	—	
Oklahoma								
Ardmore	Carter	4	−0.3	0.7	0.3	135.0	18.9	
Ardmore-Healdton	Carter	9	0.0	0.3	0.1	117.4	41.7	
Ardmore-Hewett	Carter	8	+0.8	0.5	0.2	106.6	15.5	
Bessie	Washita	1	−2.7	—	—	141.5	—	
Billings	Noble	3	−2.4	0.8	0.6	54.8	4.1	
Blackwell	Kay	2	+2.1	0.8	0.5	47.6	2.7	
Braman	Kay	3	+0.7	2.5	1.5	48.7	12.3	
Burbank	Osage	3	−0.2	0.8	0.4	48.4	8.4	
Covington	Garfield	1	−2.0	—	—	51.7	—	
Cromwell	Seminole and Okfuskee	9	+1.3	0.4	0.1	51.4	1.7	
Davenport	Lincoln	1	+0.3	—	—	113.4	—	
Dilworth	Kay	11	−0.6	0.3	0.1	54.0	3.7	
Drumright	Creek	28	−0.8	0.8	0.2	78.8	18.9	
Glenn pool	Creek	19	+1.4	0.9	0.2	40.4	2.9	
Holdenville (23)	Hughes	1	−1.8	—	—	52.9	—	
Hubbard	Kay	1	−1.2	—	—	48.4	—	
Morris	Okmulgee	1	0.0	—	—	39.2	—	
Newkirk	Kay	1	−0.5	—	—	44.2	—	
Okemah	Okfuskee	4	−0.9	2.3	1.1	41.2	2.4	
Oklahoma City	Oklahoma	3	−3.1	1.7	1.0	137.6	16.5	
Papoose	Okfuskee	4	−1.0	1.5	0.8	49.1	3.8	
Perry	Noble	1	+1.2	—	—	55.0	—	
Sasakwa	Seminole	2	−0.2	0.8	0.5	67.3	14.5	
Seminole	Seminole	19	−0.7	0.9	0.2	82.6	15.9	
Shamrock	Creek	1	—	—	—	86.4	—	
Tonkawa	Kay	15	−3.1	1.4	0.4	55.7	3.9	
Walters	Cotton	10	−1.0	0.3	0.1	117.6	10.9	
Wewoka	Seminole	5	+0.6	0.3	0.1	48.3	3.6	
Yale	Payne	1	—	—	—	54.3	—	
Oregon								
Astoria	Clatsop	1	−0.9	—	—	66.5	—	
Burns	Harney	1	−7.9	—	—	17.1	—	100 to 300 ft.
Klamath Falls (near)	Klamath	3	−2.4	2.3	1.4	25.7	—	
Medford	Jackson	2	−4.3	0.9	0.6	67.5	14.5	
Merrill	Klamath	1	−2.8	—	—	40.5	—	
Vale	Malheur	1	−8.7	—	—	19.6	—	
Pennsylvania								
Gaines Junction	Tioga	1	−1.8	—	—	94.3	—	
Johnstown	Westmoreland	1	−0.7	—	—	108.8	—	
Long Bridge	Westmoreland	3	+2.1	0.3	0.2	71.0	3.5	
McDonald	Washington	1	−4.3	—	—	130.9	—	
McKeesport	Allegheny	1	+0.2	—	—	80.0	—	
Texas								
Bastrop	Bastrop	1	−7.0	—	—	48.2	—	
Big Lake	Reagan	19	−2.9	1.0	0.2	128.2	28.2	
Blue Ridge	Fort Bend	7	−1.7	0.7	0.3	34.8	13.7	

TABLE III (*Continued*)

Town or Field	*County*	*No. of Wells*	*e*	*r*	r_0	*1/b Ft.-°F.*	*Range of 1/b*	*Remarks*
Boggy Creek	Anderson	3	−2.1	0.5	0.3	37.7	4.7	
Bonham	Fannin	1	−2.0	—	—	43.9	—	
Callisburg	Cooke	1	−0.6	—	—	103.0	—	
Canadian	Hemphill	1	−2.3	—	—	125.9	—	
Dale	Caldwell	1	−1.1	—	—	46.6	—	
Damon	Brazoria	1	−4.8	—	—	69.7	—	
Del Rio	Val Verde	2	−9.1	4.5	3.2	71.8	13.3	
Smith Ranch	De Witt	1	−1.7	—	—	57.0	—	
Dickens	Dickens	1	−3.4	—	—	97.7	—	
Eastland	Eastland	1	−3.8	—	—	56.8	—	
Edwards	Val Verde	1	−1.9	—	—	79.9	—	
Electra	Wichita	1	−0.8	—	—	86.3	—	
Ennis	Ellis	1	−5.4	—	—	58.3	—	
Ferris	Ellis	1	−1.1	—	—	49.2	—	
Graford	Palo Pinto	1	−3.3	—	—	57.6	—	
Graham	Young	2	−4.6	2.4	1.7	60.5	10.9	
Grand Saline salt dome	Van Zandt	4	−2.7	1.3	0.6	42.3	—	
Greenville	Hunt	1	−1.7	—	—	51.2	—	
Guthrie	King	1	−3.1	—	—	93.6	—	
Humble oil field	Harris	30	+0.8	1.6	0.3	30.8	15.5	
Independent oil field	Upton	1	−5.0	—	—	107.9	—	
Leonard	Fannin	1	−2.4	—	—	55.6	—	
Long Point salt dome	Fort Bend	8	−1.2	0.3	0.1	33.2	9.4	
Luling	Caldwell	4	−4.0	2.5	1.3	48.8	14.1	
Lytton Springs	Caldwell	7	−1.2	0.4	0.2	39.4	1.3	
Mexia oil field	Limestone	6	−4.9	2.5	1.0	47.7	9.3	
Muenster oil field	Cooke	1	+3.2	—	—	73.5	—	
Odessa	Midland	1	−5.1	—	—	144.2	—	
Ozona	Crockett	1	−0.9	—	—	97.1	—	
Panhandle area	Gray-Roberts-Carson	6	−4.8	2.5	1.0	117.8	39.1	
Pierce Junction oil field	Harris	3	−6.3	3.8	2.2	59.7	0.7	
Powell oil field	Navarro	14	−15.0	6.0	1.6	52.1	15.5	
Ranger	Eastland	5	−2.8	0.6	0.3	47.1	4.0	
Rosewood	Upshur	1	−5.3	—	—	51.3	—	
Sherman	Grayson	2	1.1	0.0	0.0	65.9	5.0	
St. Jo	Montague	1	+1.8	—	—	86.2	—	
Thrifty	Brown	1	−4.1	—	—	61.0	—	
Waco	McLennan	2	−3.9	1.7	1.2	48.5	4.5	
Wolfe City	Hunt	2	−0.3	0.7	0.5	53.5	2.4	
Wortham	Freestone	2	−10.9	0.8	0.6	48.3	3.5	
Washington								
Ballard Station	King	1	+1.8	—	—	107.7	—	
Benton City	Benton	1	−5.5	—	—	44.1	—	
Moclips	Grays Harbor	1	+3.1	—	—	101.6	—	
West Virginia								
Bridgeport	Harrison	1	−2.3	—	—	85.7	—	
Fairmont	Marion	1	−1.5	—	—	80.4	—	
Grantsville	Calhoun	1	0.0	—	—	86.8	—	
Mannington	Marion	1	−0.3	—	—	72.9	—	
Spencer	Roane	2	−0.3	1.0	0.7	90.2	—	
Volcano	Wood	2	−0.3	0.4	0.3	114.8	2.7	
Wyatt	Harrison	1	−1.5	—	—	92.1	—	
Wyoming								
Big Muddy	Converse	4	−5.4	1.6	0.8	60.6	12.1	
Cody	Park	2	−7.9	0.5	0.3	56.5	10.3	
Grass Creek	Hot Springs	3	−2.0	0.3	0.2	50.7	1.1	
Lance Creek	Niobrara	3	−6.7	0.4	0.2	41.2	1.7	
Lost Soldier	Sweetwater	3	−3.3	0.7	0.4	22.3	8.7	
Pine Mountain	Natrona	1	+0.5	—	—	30.1	—	
Rawlins	Carbon	4	−2.3	0.3	0.1	58.8	22.9	
Rock River	Carbon	3	−3.0	1.2	0.7	66.6	16.5	
Salt Creek	Natrona	26	−3.4	1.3	0.2	40.1	14.5	
Teapot	Natrona	1	−2.8	—	—	44.8	—	
Thermopolis	Hot Springs	9	−5.8	0.6	0.2	22.3	1.1	
Thermopolis (near)	Hot Springs	1	−7.3	—	—	56.4	—	
Thermopolis (near)	Hot Springs	1	−4.8	—	—	68.6	—	

The quantity e in the table represents the excess of soil temperature over air temperature (a-a, in Figs. 3 and 13). A negative sign precedes this quantity when the rock temperatures are higher than the annual mean air temperatures. Conversely, a positive sign precedes the tabular value when the reverse condition exists. The probable error of an observation of weight unity is represented by r and the probable error of the mean is represented by r_0.

The tabular values of the reciprocal gradient $1/b$ were computed by reciprocating the mean values of the gradient b. To obtain the range of $1/b$, the value of $2r$ for b was added to and subtracted from b. The mean of the differences between $1/b$ and the reciprocal of the two preceding values was selected to represent the range of $1/b$. For example, the table shows that the values of $1/b$ for Birmingham, Alabama, fall between the limits 88.7 and 104.9. This method of procedure is a fairly satisfactory method of presenting the data in a very condensed form. For a small number of observations, the indicated range is frequently too large.

Each value of $1/b$ in the table is recorded on the map of the United States (Fig. 5). Depths are limited to 1,000 feet, or less.

The map shows clearly that the temperatures are uniformly low in the Appalachians. There are no areas of high temperatures. In the Rockies, the temperatures vary from the extremely high to the extremely low. Irregularities over large areas rather than uniformity is the rule. In southeastern New Mexico and western Texas, including the Panhandle, extraordinarily low temperatures prevail. In Wyoming, the temperatures vary from the extremely high to a moderate average. That is, Wyoming is a high-temperature area. Likewise, eastern Texas, Oklahoma, and Kansas, southern California and Arkansas, and northern Louisiana may be characterized as areas of high to moderately high temperatures. A more detailed study of the areal and local distribution of temperatures is given in *Problems of Petroleum Geology*.[4]

As a further means of summarizing and interpreting the data, let us consider the temperature distributions over regional and local areas.

Figure 6 is a reproduction of McCutchin's (25) map showing the general trend of temperatures over a distance of approximately 100 miles in central Oklahoma, extending in a southeasterly direction from Oklahoma City to Wewoka. Another map by McCutchin, not here represented, shows a similar trend of the isothermal surfaces extending from Oklahoma City in a northeasterly direction to Sapulpa.

[4] A sequel to *Structure of Typical American Oil Fields*. In manuscript.

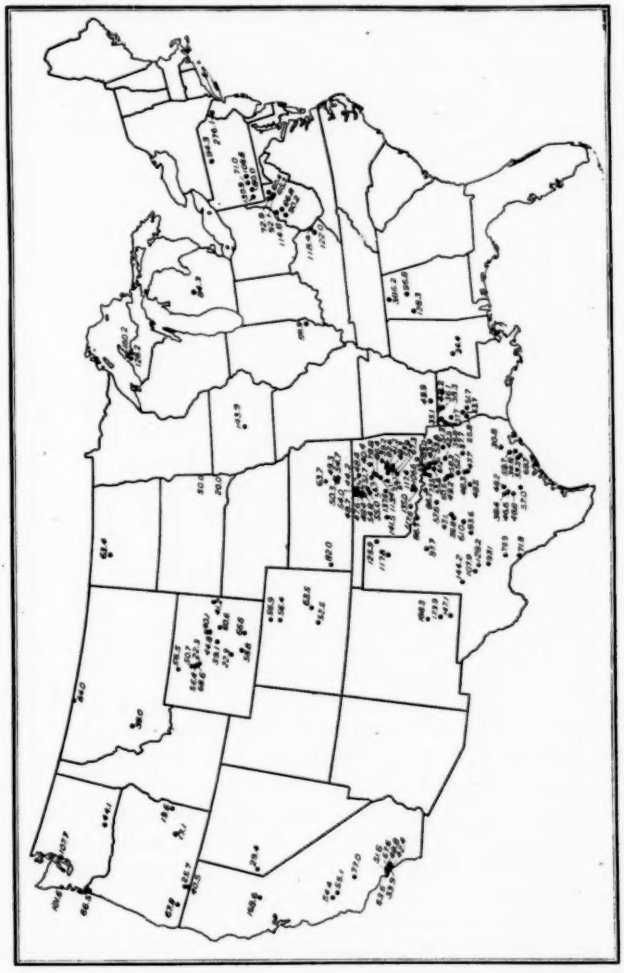


FIG. 5.—Values of $1/b$ expressed in feet per degree Fahrenheit.

Heald (19) has already emphasized the significance of these results in their relation to the general slope of the strata. He suggests that the isotherms may be a definite reflection of regional structure.

In order to summarize the evidence on the nature of the isotherms in local areas, five different types of structure have been selected as illustrations, namely, a fault, a salt plug, an unconformity of the granite ridge type, a sand lens, and an anticline with a large closure in which the circulation of water may be of importance.

Figure 7 shows a remarkable rise in the isotherms as the fault in the Powell oil field, Navarro County, Texas, is approached (26).

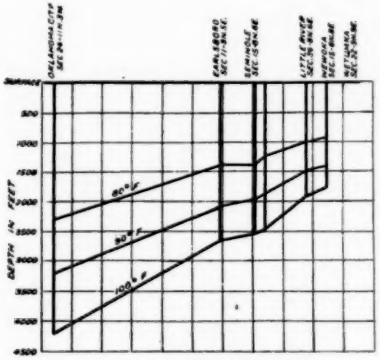


FIG. 6.—Regional variation in central Oklahoma.

As the wells in this field were in unstable temperature equilibrium, the rise is much less than is indicated on the map, but the fact that the 120° F. isotherm is within 400 or 500 feet of the producing sand justifies the belief that a real variation exists.

There appears to be no reason for questioning the large variation of temperature found by Hawtof (19) over the salt dome at Humble, Harris County, Texas (Fig. 8). According to Logan (27) this dome has a maximum diameter of 17,500 feet and a minimum diameter of 14,000 feet at the 3,000-foot salt contour.

McCutchin's (25) map of the El Dorado, Kansas, field (Fig. 9) is of interest from two standpoints. In the first place, the isotherms dip a little more steeply than the strata, and in the second place, El Dorado is a good example of the granite-ridge type of structure. This field is also representative of a simple type of unconformity (28).

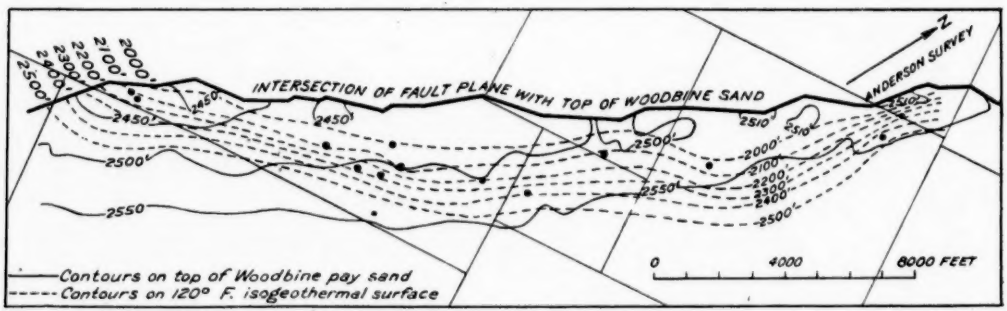


FIG. 7.—Local variation on fault, Powell oil field, Navarro County, Texas.

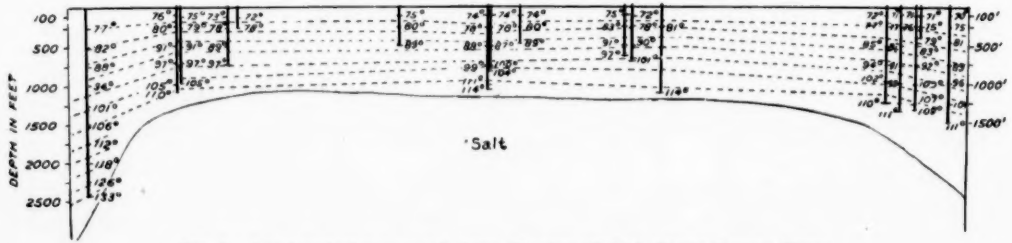


FIG. 8.—Local variation over salt dome, Humble oil field, Harris County, Texas.

Because of the difficulty experienced in obtaining wells located at a sufficient distance from edge water, the evidence on the variation of temperature over sand lenses is not very complete. However, Mc-

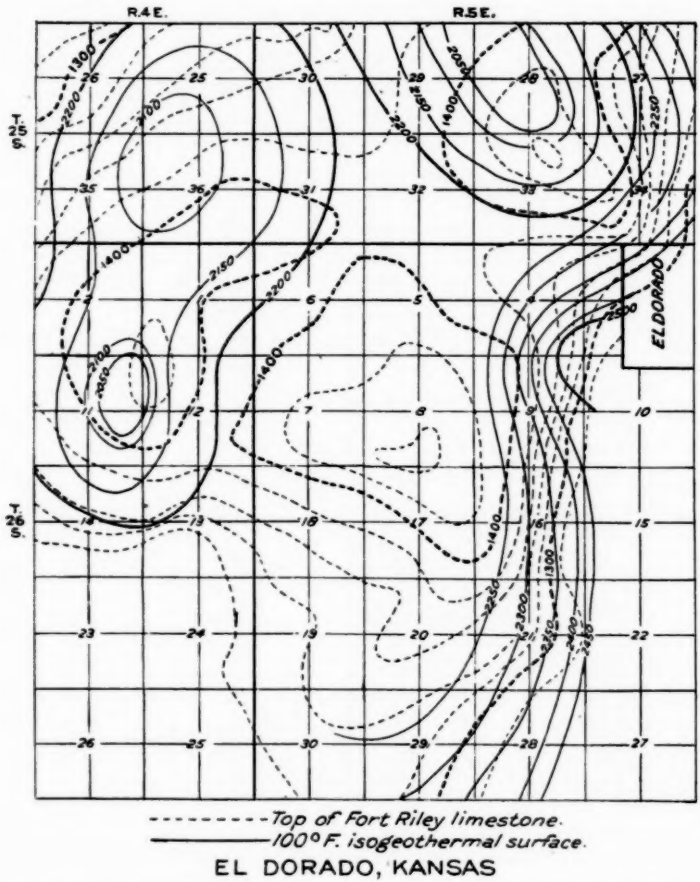


FIG. 9.—Local variation over granite ridge, El Dorado, Butler County, Kansas.

Cutchin's (29) observations in the Haverhill field, Butler County, Kansas (Fig. 10), located about 7 miles south of El Dorado, Kansas, show a well defined variation. The numbers on the right of the well locations (Fig. 10) represent the depths at which a temperature of

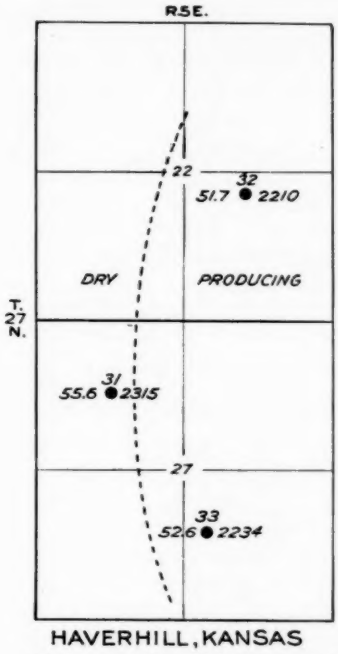


FIG. 10.—Local variation over sand lens, Haverhill, Butler County, Kansas.

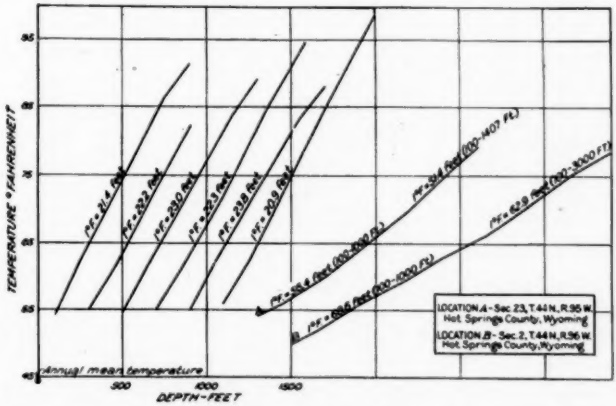

TEMPERATURE °FAHRENHEIT
DEPTH-FEET
Annual mean temperature
LOCATION A - Sec 23, T 44 N., R 95 W. Hot Springs County, Wyoming
LOCATION B - Sec 2, T 44 N., R 96 W. Hot Springs County, Wyoming

FIG. 11.—Local variation over structure in which movement of water may be of importance, Warm Springs domes, Hot Springs County, Wyoming.

100° F. is reached. The numbers on the left of the locations represent feet per degree Fahrenheit.

Very rapid rates of temperature increase have been found at Lost Soldier and Thermopolis, Wyoming. At Thermopolis, the writer made tests in 9 wells located on the tops of the two Warm Springs domes, Hot Springs County, Wyoming. The depth-temperature curves are practically the same in all of the wells. Six of the curves are shown in Figure 11. All of the curves in the figure have been drawn on the same scale, but the origin for each curve has been displaced to the right for the sake of clearness in representation. The two wells in which curves *A* and *B* were obtained are located 10 or 12 miles northwest of the Warm Springs domes. As the Big Horn hot springs, one of the largest hot springs in the world, is about 5 miles west of the oil fields, the movement of water over the domes may be of very great importance.

CAUSES OF TEMPERATURE VARIATIONS

Three distinct types of variation have been discovered, namely, variation in the vertical, and variations over both large and small areas.

The dependence of the distribution of temperatures in the vertical on the porosity of the rocks and on the rise of air temperatures since the ice age is discussed in previous paragraphs. The precision with which the rock temperatures are adjusted to the air temperatures above them is indicated by the fact that the mean of 514 values of e (Table III), distributed throughout the United States, exclusive of the Powell oil field, Texas, and the oil fields of California, is -1.54°F. The data from the Powell oil field are believed to be erroneous. The mean value of e for 144 wells in the California oil fields is -8.44° F. The cause of this large value is not known. By assuming it to be an error, and adding 1° F. to the observed annual mean temperature of the air, the following corrected reciprocal gradients are obtained.

Bakersfield	53.8	Long Beach	43.1
Coalinga	45.9	Santa Fe Springs	45.7
Fullerton	46.9	Seal Beach	42.6
Huntington Beach	34.6	Whittier	48.2
Kettleman Hills	42.6		

As these numbers are much less than the corresponding numbers in Table III, it follows that the evidence in support of the hypothesis of a variation of temperature over these structures is greatly strengthened if it is assumed that the large value of e is due to drilling and producing operations.

Another marked variation in the vertical is shown in Figure 4. Here the rise in the depth-temperature curve is almost imperceptible

to a depth of about 300 feet. A similar condition exists at Birmingham, Alabama. Barring the possibility of abnormal conditions in the well, which seems rather improbable, the flattening of the curves may be due to ground water.

In summarizing the remaining evidence of the preceding sections, it can be said that it tends to show that regional variations exist; and that local variations have been found on five different types of structure on which oil fields are located. They are: faults, salt domes, granite ridges (or simple types of unconformity), sand lenses, and a structure with a large closure in which the temperature may be controlled in part by the movement of water. Elsewhere (31), the writer has discussed the evidence in regard to the variation of temperature over structures of both large and small closure in which the movement of water is probably of no importance.

With regard to regional variations, an hypothesis of vertical uplift proposed by Nevin and Sherrill (32) to explain the origin of certain local uplifts in north-central Oklahoma is of fundamental importance. According to their hypothesis, regional tilting of a rock mass by vertical forces has resulted in producing local uplifts over areas of weakness in the pre-Cambrian complex. By referring to Figure 6, it will be noted that the temperatures rise gradually as the depth to the granite diminishes, as we pass from Oklahoma City to Wewoka, and, furthermore, the highest temperatures are found over the oil fields, the areas in which, according to Nevin and Sherrill, the hot rocks have been pushed upward through the basement complex. The processes of uplift thus proposed by Nevin and Sherrill suffice to explain both local and regional variations of temperature in certain areas. Another important contribution to our hypothesis of regional variations was made a number of years ago by N. H. Darton (33). His map shows clearly that the temperature gradients in eastern South Dakota increase as the depth to the granite or quartzite diminishes. As shown on the map (Fig. 5), the reciprocal gradients vary from 1° F. in about 20 feet to 1° F. in more than 50 feet.

In order to reach a conclusion in regard to other causes of local variations, let us consider the possibilities of thermal conductivity, chemical reactions, and radioactivity.

First, let us consider the differences in the values of $1/b$ at Haverhill, Kansas (Fig. 10), from the standpoint of thermal conductivity and the generation of heat from chemical reactions.

The sand lens can be regarded as a buried disk that is a very poor conductor of heat, for, under the same conditions, water transmits 4 times and limestone 14 times as much heat as petroleum. The correct

solution of the problem can be obtained by constructing the isogeotherms. By proceeding in this way, Strong (34) has shown that the general effect of a poorly conducting disk is to increase the gradients immediately above and below the disk.

Let us now attempt to estimate the rate at which heat must be developed by chemical reactions within the disk in order to maintain the differences in the values of the reciprocal gradients ($1/b$) which were found at Haverhill. The mean of the two reciprocal gradients on the producing area is 52.15 feet per °F, which compared with the one

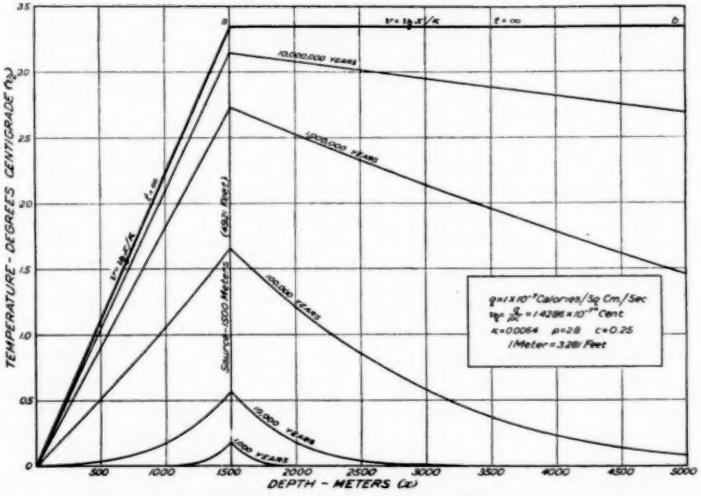


FIG. 12.—Rise in temperature due to heat source at 1,500 meters (4,921 feet).

obtained on the nonproducing area, 55.6 feet per °F., corresponds with a temperature difference of 2.97° F. (1.65° C.) at a depth of 762 meters, 2,500 feet. From the diagram (Fig. 12), (35) the maximum rise in temperature due to a heat source at a depth of 762 meters is about 1.7° C., and as is also shown in the diagram, this constant temperature difference can be maintained by the generation q of 1×10^{-7} calories per square centimeter per second, or, 3.16 calories per square centimeter per year (2,932 calories per square foot per year) in a thin stratum of rock. As the value, 1.7° C., is a sufficiently close approximation to the value 1.65° C., it may be assumed that the value of q has been determined with sufficient accuracy for our purpose. Let us now estimate for comparison with our calculated value of q, the quantity

of heat that can be obtained by the oxidation of petroleum in its natural state. Let us assume that the heat-generating disk is 100 feet in thickness and that 1/3 of the entire volume is crude oil. Then a column of rock, 1 square centimeter in cross section and 100 feet in length, contains about 900 grams of oil, and as the heat of combustion of crude oil is about 11,094 calories per gram, it follows from our preceding value of q that all of the oil would be oxidized in $(11{,}094 \times 900)/3.16 = 3.2 \times 10^6$ years. As this result is not in agreement with geological facts, we conclude that the oxidation of oil may be a contributing factor, but it is not sufficient in itself to maintain the constant temperature differences which exist at Haverhill. Werner (36) regards petroleum deposits as special sources of heat. He believes that the

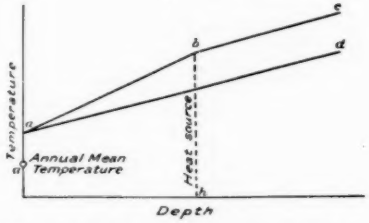


FIG. 13.—Sketch of depth-temperature curves. Heat source at *h*.

presence of carbonic acid in the gases is evidence of oxidation brought about probably by the presence of free oxygen in salt water.

In Figure 13, the line *ad* represents a depth-temperature curve on the basis of normal cooling. The excess of soil temperature over air temperature, *e*, is represented by *aa*. The line *abc* represents a depth-temperature curve when there is a source of heat at *b*. Curves of this type have been found at El Dorado, Kansas; Coalinga, California; Big Lake, Texas, and in some other fields. Ordinarily, however, the curvature is in the opposite direction.

It remains to consider the possibility that radium is a source of heat beneath anticlines. Three factors are involved, namely, transmission of heat along the strata, an excess of radium in granite as compared with the sediments, and the presence beneath the oil-bearing strata of a granitic mass that stands above the general level of the basement rocks. The problem is illustrated in Figure 14 in which the height of the granite ridge is represented by *ab*. Inspection of the figure shows that transmission of heat along the strata may result in a considerable excess of heat beneath the anticline. Two sources of heat are available. First, excess of radioactivity in the granite and, second, an increased

flow of heat from rocks that have been displaced towards the surface of the earth.

Joly's (37) values for the heat developed by radioactivity are: 16.6×10^{-14} calories per second per gram for sediments; and 30×10^{-14} for granite. This leaves 13.4×10^{-14} calories per second per gram as a source of excess heat in the granite. This estimate is based on the activity of thorium and uranium. Carrying out the calculations, we find for the excess heat developed in the granite, the value, 0.348 calories per year per square centimeter per 1,000 feet of thickness (*ab*, Fig. 14) of granite standing above the general level of the basement floor. To make an accurate calculation, it is necessary to assume a great number of heat sources and draw the curves for each source as shown in Figure 12. The sum of all of the ordinates at any point represents the

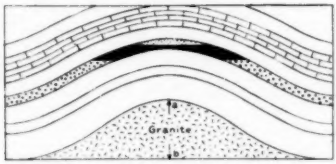


FIG. 14.—Sketch showing cross section of anticline.

temperature at that point. It will suffice for our purpose to assume that all of the heat is generated in one plane, or thin stratum; and since heat has been developed in granitic rocks since their solidification, it follows that the increment in temperature is represented by the straight line *oa* in Figure 12. The slope of the line *oa* is determined by the thermal constants of the rocks and the rate of generation of heat. Hence, it is independent of the depth to the heat source. This means that a granitic mass of height *ab* (Fig. 14), above the basement complex at El Dorado, Kansas, where the depth to the granite is only 3,000 feet, produces the same change in the gradient, other conditions being the same, as at Long Beach where the granitic mass may be buried to a depth of 20,000 feet. In other words, ridges in the basement floor are reflected by increased temperature gradients at the surface, and the change in the gradient is independent of the thickness of the sediments.

We can estimate the magnitude of the increment in the temperature or the gradient by comparing the value, 0.348 calories per year per square centimeter per 1,000 feet of thickness of granite with the value 3.156 calories per year per square centimeter for a thin stratum

at a depth of 1,500 meters (Fig. 12). The comparison shows that a thickness of 9,000 feet of granite (*ab*, Fig. 14) produces the same increment in the gradient as the heat source represented in the figure. As the increments in temperature represented in the figure are of the same order of magnitude as those found on the crests of anticlines as compared with the temperatures at the same depth near edge water, it follows that some of the excess heat beneath anticlinal structures may be due to radioactivity.

SUMMARY AND SUGGESTIONS

The importance of geothermics in large-scale problems has been illustrated by attempting to estimate the depth to the level of isostatic adjustment from observations of temperature in Moffat tunnel. By assuming the depth to the level of isostatic compensation to be given, it may be possible to make a more accurate estimation of temperatures down to that depth than has heretofore been made.

The geothermal map (Fig. 5) probably represents high temperatures over small areas rather than average temperatures over large areas. For example, the areas surrounding salt domes are probably areas of average temperature, or at most, only moderately high temperatures.

Summarizing the results of recent geothermal surveys, the evidence shows that variations of temperature have been found to be associated with salt domes, sand lenses, faults, and structures with both large and small closure. The extent to which this generalization applies is not known.

Concerning causes of temperature variations, both local and regional variations are apparently dependent on the presence of granite. This result, as applied to regional variations, was anticipated to a certain extent by Lawson (38), who foresaw the possibility of correlating temperature gradients with the granitic layers in different parts of the world. As applied to local variations, the result is in agreement with an important suggestion by Clapp (39) that the importance of the shortening of the columnar sections over anticlines is just beginning to be appreciated. The result must not be interpreted as proving conclusively that radium is the source of all of the heat escaping from the surface of the earth. Normal cooling is still a possibility that the evidence has not yet excluded.

Chemical reactions in oil-bearing strata appear to be of minor importance as heat sources.

Further calculations and experiments are needed as a means of estimating the importance of oil-bearing strata in preventing the

escape of heat from the earth, and incidentally causing changes in the thermal gradient.

Tests in one well or more drilled between Thermopolis and the Warm Springs dome would have given important evidence on the amount of heat transferred by water. With existing data (Fig. 11) and Darton's (40) description of the movement of the water, it may still be possible to reach conclusions of more or less importance.

Geothermal prospecting may succeed in certain areas. Under the most favorable circumstances it would be necessary to make tests in core drill holes extending through a period of several months in order to be sure that true rock temperatures are obtained. Ordinarily, the holes would have to be drilled to a depth in excess of 500 feet. A less depth would doubtless be required over shallow salt domes.

BIBLIOGRAPHY

1. A. S. Eddington, *Stars and Atoms*, Yale University Press, New Haven, Connecticut (1927), p. 102.
Harold Jeffreys, *The Earth*, Macmillan Company (1929), pp. 76–77.
Hans Reichenback, *Atom and Cosmos*, Macmillan Company (1933), 300 pp.
2. Charles E. St. John, "Growth in Our Knowledge of the Sun," *Ann. Rept. Smithsonian Institution*, Washington, D. C. (1930), p. 178.
3. H. N. Russell, R. S. Dugan, and J. Q. Stewart, *Astronomy*, Vol. 2, Ginn and Company (1927), p. 502.
4. Reference 1. Jeffreys, p. 144.
Arthur Holmes, "Radioactivity and Geological Time," in "The Age of the Earth," *Natl. Res. Council Bull. 80*, Washington, D. C. (1931), pp. 218 and 230.
5. C. S. Piggot, "Radium Content of Ocean Bottom Sediments," *Amer. Jour. Sci.*, Vol. 25 (March, 1933), pp. 229–38. (The high concentration of radioactive material is here attributed to oxidation and other causes.)
6. L. H. Adams, "Temperatures at Moderate Depths within the Earth," *Jour. Washington Acad. Sci.*, Vol. 14 (December 4, 1924), pp. 459–72.
7. Harold Jeffreys. See reference 1, p. 154.
8. William Bowie, "Isostasy. The Figure of the Earth." *Natl. Res. Council Bull. 78* (1931), p. 108.
9. Reference 1, p. 151.
10. Reginald A. Daly, "The Depths of the Earth," *Science*, Vol. 77 (January 27, 1933), pp. 95–102.
11. William Bowie, "A Gravimetric Test of the 'Roots of Mountains' Theory," *U. S. Coast and Geod. Survey Serial 291* (1924), pp. 3–8.
———, "Notes on the Airy or 'Roots of Mountains' Theory," *Science*, Vol. 63 (April 2, 1926), pp. 371–74.
See also reference 7.
12. Osmond Fisher, *Physics of the Earth's Crust*, Macmillan Co. Second Edition (1889), pp. 222–29.
13. Charles H. Lees, "On the Shapes of the Isogeotherms under Mountain Ranges in Radioactive Districts," *Proc. Roy. Soc. London*, Vol. A. 83 (January 8, 1910), p. 346.
14. Harrison E. Patten, "Heat Transference in Soils," *U. S. Bur. Soils Bull. 59* (1909). 54 pp.
15. Joseph Prestwich, *Collected Papers on Some Controverted Questions of Geology*, Macmillan Company (1895), p. 241.
16. N. W. Bass, "Geologic Investigations in Western Kansas," *State Geol. Survey Kansas. Bull. 11* (1926), p. 83.
17. W. W. Rubey, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: A Discussion," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 6 (June, 1927), pp. 621–32.

18. A. C. Lane, "Geophysical Abstracts," *Min. and Met.*, Vol. 9 (1928), pp. 461–62.
———, "Geotherms of Lake Superior Country," *Bull. Geol. Soc. Amer.*, Vol. 34 (1923), pp. 703–20.
———, "Temperatures of the Copper Mines," *Michigan Geol. Biol. Survey*, Vol. 2 (1909), pp. 757–73. (The Keweenaw series.)
———, "Geotherms," *Jour. Washington Acad. Sci.*, Vol. 20 (1930), pp. 450–54.
L. R. Ingersoll, "Geothermal Gradient Determinations in the Lake Superior Copper Mines," *Physics*, Vol. 2 (March, 1932), pp. 154–59.
James Fisher, L. R. Ingersoll, and Harry Vivian, "Recent Geothermal Measurements in the Michigan Copper District," *Amer. Inst. Min. Met. Eng. Tech. Pub. 481* (New York Meeting, February 1932), pp. 1–11.
19. "Earth Temperatures in Oil Fields," *Amer. Petrol. Inst. Bull. 205* (New York, October, 1930), 139 pp.
K. C. Heald, "The Study of Earth Temperatures in Oil Fields on Anticlinal Structure."
C. E. Van Orstrand, "Description of Apparatus for the Measurement of Temperatures in Deep Wells; Also, Some Suggestions in Regard to the Operation of the Apparatus, and Methods of Reduction and Verification of the Observations."
J. A. McCutchin, "Determination of Geothermal Gradients in Oil Fields Located on Anticlinal Structures in Oklahoma."
E. M. Hawtof, "Results of Deep Well Temperature Measurements in Texas."
A. C. Carlson, "Geothermal Condition in Oil Producing Areas of California."
20. W. D. Johnson, Jr., "Geothermal Gradient at Grass Valley, California," *Jour. Washington Acad. Sci.*, Vol. 22 (1932), pp. 256–71.
21. S. W. Beyer, *Iowa Agricultural College Water Supply*. Press of *Ames Times*, Ames, Iowa (May, 1897).
22. N. H. Darton, "Geothermal Data of the United States," *U. S. Geol. Survey Bull. 701* (1920), pp. 58–59.
23. George F. Becker, "Geology of the Comstock Lode and the Washoe District," *U. S. Geol. Survey. Mon. 3* (1882), pp. 246–52.
24. Hugh D. Miser, "Temperature of Oklahoma's Deepest Well," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8, No. 4 (July–August, 1924), pp. 525–26.
25. John A. McCutchin. See reference 19.
———, "Determination of Geothermal Gradients in Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 5 (May, 1930), pp. 535–55.
26. F. B. Plummer and E. C. Sargent, "Underground Waters and Subsurface Temperatures of the Woodbine Sand in Northeast Texas," *Univ. Texas. Bull. 3138* (October 8, 1931), p. 92.
27. Jack Logan, "Deep Sand Development Opens New Possibilities for Humble Fields," *Oil Weekly*, Vol. 56 (January 17, 1930), p. 27.
28. John R. Reeves, "El Dorado Oil Field, Butler County, Kansas," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 160–67.
29. See reference 25.
30. A. J. Collier, "Oil in the Warm Springs and Hamilton Domes, Near Thermopolis, Wyoming," *U. S. Geol. Survey Bull. 711-D* (1920), pp. 61–73.
31. C. E. Van Orstrand, "Some Evidence on the Variation of Temperature with Geologic Structure in California and Wyoming Oil Districts," *Econ. Geol.*, Vol. 21 (March–April, 1926), pp. 145–65.
———, "On the Correlation of Isogeothermal Surfaces with the Rock Strata," *Physics*, Vol. 2 (March, 1932), pp. 139–53.
———, "Some Comments on the Measurement and Interpretation of Deep Earth Temperatures," *Gerlands Beitrage zur Geophysik*, Band 3 (March, 1933), pp. 261–81.
32. C. M. Nevin and R. E. Sherrill, "The Nature of Uplifts in North-Central Oklahoma and Their Local Expression," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (January, 1929), pp. 23–30.
33. N. H. Darton, "Geothermal Data of the United States," *U. S. Geol. Survey Bull. 701* (1920), opp. p. 80.
34. M. W. Strong, "Geothermal Phenomena and Geological History with Special Reference to Old Structures in Geothermal Equilibrium," *Jour. Inst. Petrol. Tech.* (London), Vol. 16 (1930), pp. 889–901.

35. C. E. Van Orstrand, "On the Flow of Heat from a Rock Stratum in Which Heat is Being Generated," *Jour. Washington Acad. Sci.*, Vol. 22 (December 19, 1932), pp. 529–39.

36. H. Werner, "Geothermics as a Means of Locating Petroleum Deposits," *Petrol. Times* (London), Vol. 23 (April 10, 1930), pp. 713–14.

37. John Joly, *Surface History of the Earth*, Oxford (1930), p. 69.

38. Robert W. Lawson, "Radioactivity and the Heat of the Earth," *Nature*, Vol. 119, No. 2 (May 14, 1927), p. 704.

39. Frederick G. Clapp, "Role of Geologic Structure in the Accumulation of Petroleum," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 694–95.

40. N. H. Darton, "The Hot Springs of Thermopolis, Wyoming," *Jour. Geol.*, Vol. 14 (1906), pp. 194–200.

H. C. Boydell, "Temperature of Formation of an Epi-Thermal Ore Deposit," *Inst. Min. Met. Eng. Bull. 331* (April, 1932), pp. 19–43; Discussion, *332* (May, 1932), pp. 25–39; *333* (June, 1932), pp. 13–19.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 39-62, 17 GRAPHS

EARTH RESISTIVITIES AT DEPTHS LESS THAN ONE HUNDRED FEET[1]

W. D. KELLER[2]
Columbia, Missouri

ABSTRACT

Empirical data on the resistivities of different kinds of rocks to depths of 100 feet were obtained under known field conditions. The resistivity-depth relations are plotted in the conventional manner.

A series of graphs shows the resistivity of the rocks along three geologically known sections across the Cap-au-Gres fault in northeast Missouri, the adjacent rocks across the fault surface being different in each case.

INTRODUCTION

While prospecting for near-surface deposits of clay and hematite in central Missouri during 1930 and 1931, the writer's attention was turned to the use of the earth-resistivity method of geophysical prospecting. Being wholly unfamiliar with the technique, the writer found it necessary to read as much of the literature available on the subject at that time as was possible. It was disappointing, however, to find hardly a single systematic study of the elementary principles published which would be applicable to work at shallow depths.

Consequently, several weeks of field work was done simply to obtain, empirically, typical resistivity values over shale, sandstone, limestone, alluvium, a known thickness of one type of rock over another, and other relationships, at depths less than 100 feet. It was believed that a determination of these resistivity values in the field under known conditions would be of more practical value than observations on miniature "synthetic" laboratory structures. After obtaining data on known conditions, it was proposed to apply them to the unknown. Since similar data have not appeared in the literature to date, the writer offers his results in the hope that they may be of aid to others.

The work was carried on in 1930 and 1931, as previously stated, and was done wholly within Missouri. The specific location of each observation is indicated in its write-up.

Through the courtesy of the A. P. Green Fire Brick Company,

[1] Manuscript received, May 15, 1932.

[2] Assistant professor, department of geology and geography, University of Missouri. Introduced by W. A. Tarr.

Mexico, Missouri; Jones and Turner, mining contractors, Linn, Missouri; and the physics department, University of Missouri, the writer borrowed and assembled a set of equipment, and obtained data which would otherwise not be available. Professor W. A. Tarr, of the department of geology, University of Missouri, offered suggestions and criticisms.

APPARATUS AND METHOD

The method followed was the simple Wenner 4-electrode hook-up, described in some of the handbooks[3] on geophysical prospecting. In addition, a supplementary potential electrode, as proposed by Lee and Swartz,[4] was frequently used for tapping in the center of the circuit. As a ready-made resistivity measuring set was not available with the funds at hand for the work, a modified Gish-Rooney set was assembled by using a standard 0–75 milliammeter, student potentiometer, 90-volt radio B battery, and a locally constructed circuit reversing commutator driven by a 6-volt motor.

Ordinary surveyor's tapes were used to measure the electrode separation. They were laid off in feet, and as a convenience the computations of resistivity were reported, not in ohms per centimeter cube, the usual method, but in a field unit, ohms per foot cube. At each observation the electrode spacing in feet was selected, the current in milliamperes and the potential in millivolts read, and the field resistivity unit, r, computed from the equation:

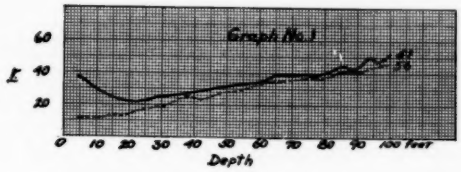
$$r = a\frac{E}{I}$$

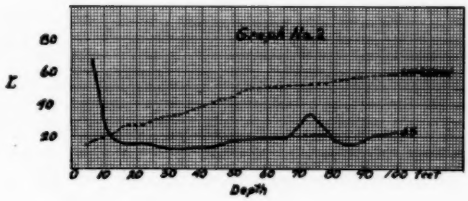
where a is the electrode separation in feet, and E and I, millivolts and milliamperes, respectively. It is obvious that the computation was made with the greatest ease in the field at once, and was available for use there on the ground. Since an intelligent selection of the location or procedure of the next set-up may be governed to a large extent by the results at the previous one, and since this advantage is lost if calculations are delayed until the office is reached, the advantage of a simple and easily calculated unit is apparent.

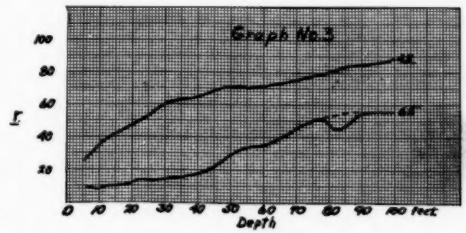
In accordance, all data embodied in this report are in terms of the aforementioned field resistivity unit.

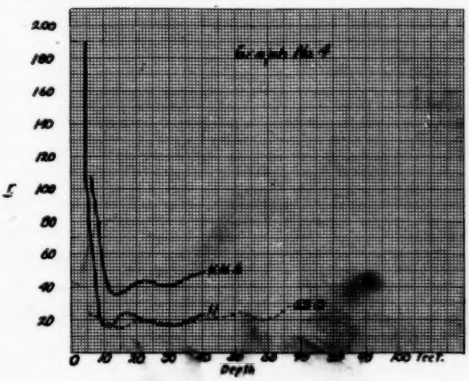
[3] A. S. Eve and D. A. Keys, *Applied Geophysics*, London, Cambridge University Press (1929), p. 83. *Geophysical Prospecting, 1929, Amer. Inst. Min. Met. Eng.*, New York, p. 54.

[4] F. W. Lee and J. H. Swartz, "Resistivity Measurements of Oil-Bearing Beds," *U. S. Bur. Mines Tech. Paper 488* (1930).


Graph No. 1
60
40
20
R
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth


Graph No. 2
60
40
20
R
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth


Graph No. 3
100
80
60
40
20
R
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth


Graph No. 4
200
180
160
140
120
100
80
60
40
20
R
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth

TYPICAL RESISTIVITY CURVES

To obtain typical resistivities of the various kinds of rock at depths to 100 feet, a set-up was made over a particular kind of rock having a minimum thickness of at least 100 feet and readings were taken at increasing electrode spacings. The resistivity unit for each spacing (or depth) was computed and the results plotted graphically, as shown in the following curves. Depth in feet is shown on the abscissa and resistivity on the ordinate.

It may be pointed out that the resistivity indicated for the 50-foot depth, for example, is not for the rock at that depth alone, but includes all rock between, adjacent to the electrodes, and to a depth of 50 feet.

ALLUVIUM

Graph No. 1 shows the range of the resistivity of alluvium in the simple resistivity units up to 100 feet in depth. The stations were located on the Mississippi River flood plain near Foley, Lincoln County, Missouri. The alluvium of curve 51 is underlain by Jefferson City dolomite and that of 56 by St. Peter sandstone. The curves are essentially the same. The slight upturn of the upper one at less than 20-foot depths was due to dry soil on the edge of a corn field.

In all resistivity curves of fine alluvium obtained by the writer the range is low, usually under 75 units. The two curves given are typical.

In high or dry gravel banks the resistivity may be considerably higher.

The resistivity of sedimentary rocks seems normally to increase with depth, and the higher the resistivity, the faster the increase.

SHALE

Curve 63 on Graph No. 2 is typical of the resistivity of an ordinary shale, the Grassy Creek shale, located about 3.5 miles southwest of Foley, Missouri.

The resistivity of slightly sandy shale is shown on curve *VH* 450 *W*. It was taken in the Cherokee formation, 3 miles east of Linn, Osage County, Missouri. The curve is also typical and is similar to 63 and 65.

Curve 65, Graph No. 3, shows the resistivity of Maquoketa shale measured on a gentle slope above a creek bed a few hundred feet north of the location of curve 63. The higher trend of 65 over 63 is probably due to the fact that the Maquoketa is much more calcareous and sandy than the Grassy Creek.

Shale of still higher resistivity is shown by curve 42. However, it does not differ in composition from 65, but is the same Maquoketa measured on a high dry creek bank where little soil mantled the shale outcrop. The writer shows this as an excellent illustration of the effect of the position of a set-up with reference to the drainage and water table on the resistivity of the rocks. It seems unquestionably true that the higher resistivity of 42–65 is due to an unsaturated condition prevailing in the vertical high creek bank. As a precaution the measurement of 42 was taken sufficiently far back from the face of the bank to obviate any effects of a limited conductor, as would be the case if the set-up had been made on the brink. In that position half of the normal current conductor space would have been air instead of rock and a high resistivity would have resulted.

The measurement of shale under ordinary topographic conditions is represented by 65 and that curve is taken as normal. The other should be kept in mind because it may occur under some conditions of prospecting. A similar effect was also shown by limestone.

FIRE CLAY

Thirty feet of Pennsylvanian fire clay (Cherokee formation) lying below 15 feet of reworked glacial sand and clay is represented by curve 53 *D* on Graph No. 4. Its electrical properties are so similar to those of shale that the two rocks can not be differentiated by resistivity methods. Unfortunately also, from an economic standpoint, the overburden on this deposit had a resistivity similar to the clay, and the resistivity method was of no value in prospecting here.

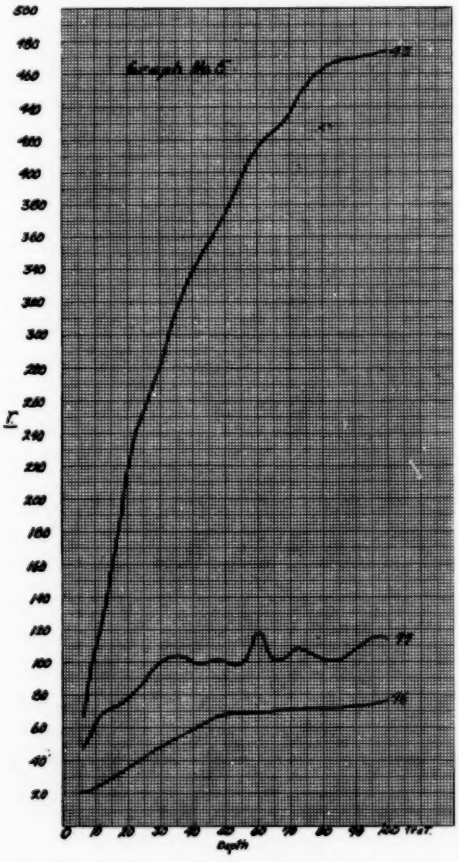
The resistivity of diaspore clay is shown in the flat part of curve *V. H.* 6. It is normally slightly higher than that for shale, but the difference is hardly great enough to enable one to differentiate between the two on this basis alone. The geology of the region and effects of the sandstone rim rock must be taken into consideration in the electrical prospecting for diaspore.

The steep parts of curves *V. H.* 6 and 11 represent resistivities to depths of about 12 to 13 feet, the transition from overburden to solid rock. Both locations, *V. H.* 6 for diaspore, and 11, a hematite prospect, were drilled and found to check electrical predictions exactly as far as overburden and solid rock relationship were concerned. However, the flat part of 11 went into only slightly ocherous, sandy shale and not into hematite which the lessees desired.

The high surface resistivities are due to the nature of the overburden, a cherty gravelly soil that drains readily, especially in the hills of Osage County, where these locations were run. Similarly, glacial gravels that are fairly clean from clay show high resistivities.

LIMESTONE

The resistivity of the Kimmswick limestone is shown on Graph No. 5 under three different conditions. First, curve 77, the limestone with no soil cover, was measured where it was cleanly exposed in the



bed of a small creek one mile north of Elsberry, Lincoln County. The electrodes were laid directly on the limestone in the shallow, almost quiet water of the stream.

The next set-up, 76, was made about 35 feet north of 77, where the same limestone was covered by about 3 feet of alluvium. The resistivity here is uniformly about 30 units less than that of 77. The writer

sees no other explanation for the lowering of the resistivity than the effect of the low resistivity alluvium. The rock was the same, the stratigraphic horizon the same, the current lines parallel, and the separation of instrument locations less than the distance of maximum current path spread so that there must have been overlap of current paths of the two set-ups; the only difference between the two locations was the 3 feet of alluvium at 76. Other determinations, some of which will be shown later, substantiate this view. The writer believes that the effect due to the thickness and nature of the mantle rock is significant and important, and can not be ignored in careful work, especially at shallow depths.

In marked contrast to 76 is 43, taken over the same formation and at about the same stratigraphic horizon, but where the limestone is exposed in approximately a 75-foot vertical river bluff. The soil was thin and the hill well drained on all sides. The resistivity has reached a maximum of 475 field units.

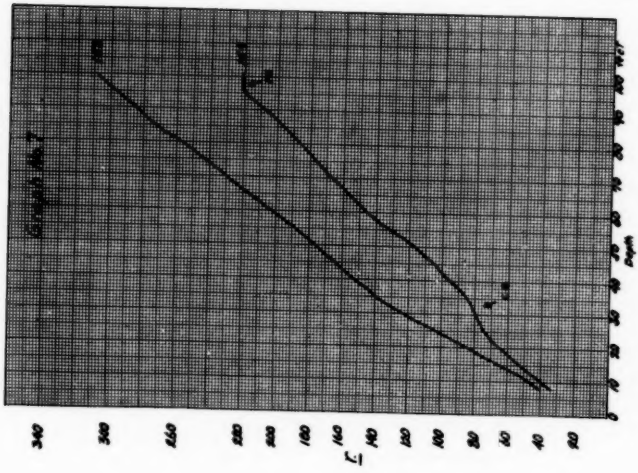
SANDSTONE

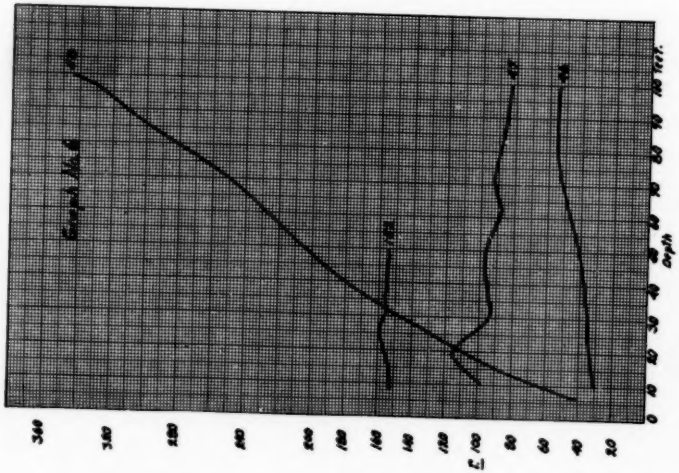
The St. Peter sandstone was studied under similar conditions to those of the Kimmswick limestone. Curve 47 of Graph No. 6 indicates the resistivity of the St. Peter in a creek bed where the electrodes were laid directly upon the sandstone in shallow water. Curve 46 indicates the resistivity of the same rock about 25 feet north of 47, where 4–5 feet of alluvium covers the sandstone. Electrodes were parallel in the two set-ups and conditions made as near identical as possible with the exception of the alluvium. The lowering of the resistivity in this case is similar to that with limestone excepting that it is more pronounced here. In fact, curve 46 could as well be taken for shale. In three other instances the writer found low resistivity values for sandstone, due once to clay impurities and for the other two presumably to a mantle of fine wet soil.

The same formation (St. Peter) at approximately the same stratigraphic horizon was run on a high bluff covered with a thin layer of sandy soil. The resistivity was high, as shown in curve 58. The writer again attributes the increase to the drainage of the sandstone, that is, lowering of the water table.

A 50-foot thickness of La Motte sandstone (Cambrian) resting on porphyry was run and its results shown in curve 152. It was located on the side of a moderately sloping stream valley mantled with about 4 feet of soil.

The location of 46 and 47 is on Big Sandy Creek, one mile west of Burr Oak, Lincoln County; 58 is half a mile west of Bethany Church, near Foley, Missouri; 152 is 5 miles west of Fredericktown, Missouri.





IGNEOUS ROCK

Curve 153 of Graph No. 7 shows the resistivity of a diabase dike 4 miles west of Fredericktown, Missouri. The instrument was then moved over to within 50 feet of the contact with the rhyolite porphyry and curve 154 run. The short flat parts occur in this curve where the current and potential electrodes moved over the contact, but the break is not sufficiently pronounced to be used to differentiate the rocks in an unknown area. The curves are given merely as examples of igneous rock resistivities.

Curve 161 of Graph No. 8 illustrates the data taken over bare rhyolite in Stouts Creek above Lake Killarney in Iron County. The resistivity is extremely high and variable.

Insufficient data were accumulated on igneous rock to justify drawing any definite conclusions, but the indication appears to be that the Gish-Rooney method of electrical prospecting can be used more satisfactorily in the stratified sediments than in the igneous.

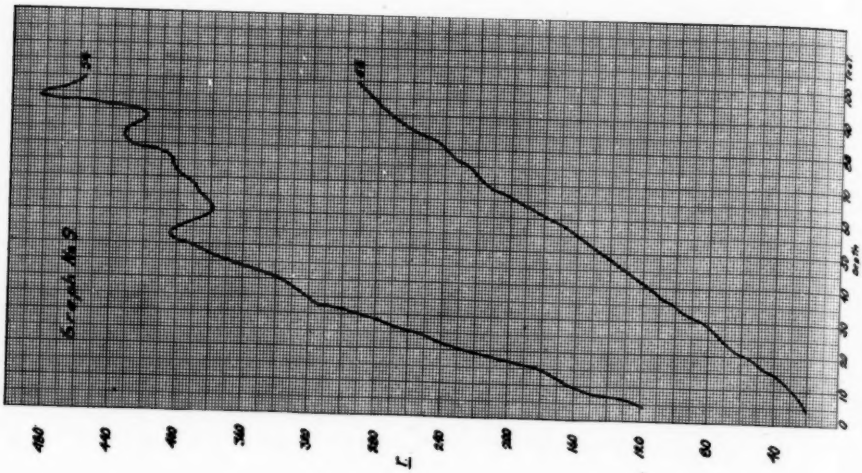
RESISTIVITY AT A QUARRY FACE

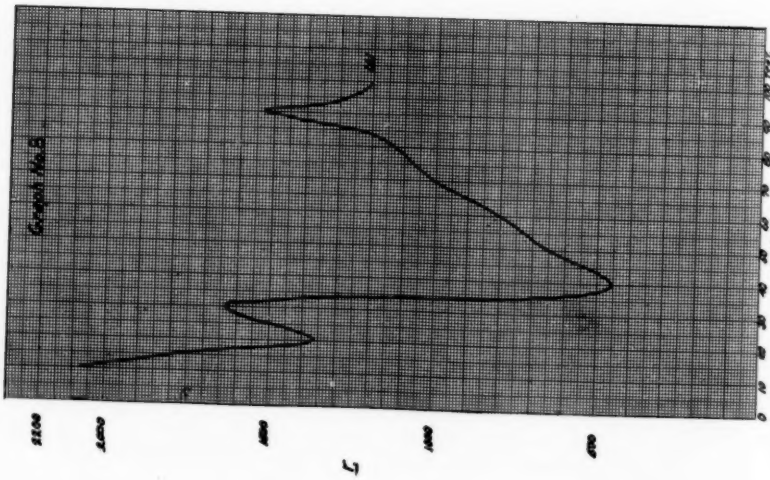
The occasion arises at times when one wishes to obtain, for the purpose of a standard or a known, the resistivity of a deposit which is exposed in a vertical face in a quarry or open mine. If a set-up is made at the edge of the face the figures obtained should theoretically not be the same as those from a set-up 150 or more feet back because half of the earth conductor has been removed at the quarry face. It would seem that the resistivity should be higher at the face because the cross sectional area of the conductor has been reduced. That this is actually true is shown by curves 53 and 54 on Graph No. 9. Curve 53 is the resistivity record of a deposit of Joachim dolomite-Plattin limestone 175 feet back of the face of a vertical bluff 100 feet high half a mile north of Foley, Missouri. Set-up 54 was next made within a few feet of the edge of the bluff and the resistivities found to be consistently 100–150 units higher than a normal set-up.

It is logical to assume that an ore deposit in this bluff would show a higher resistivity than the same ore would when wholly buried. A correction factor derived in the same manner as the foregoing should be obtained and applied wherever the same conditions are met in practice.

ADJOINING HIGH AND LOW RESISTIVITY FORMATIONS

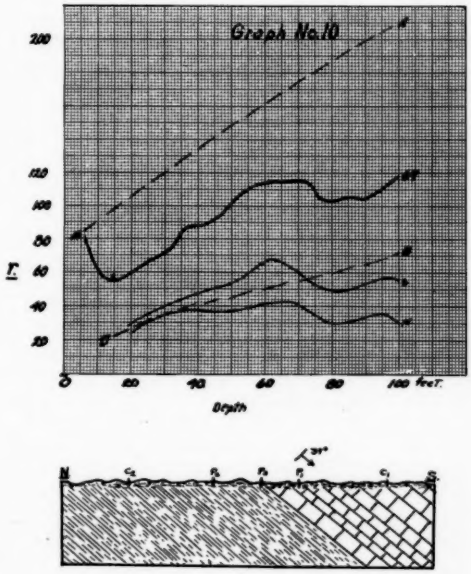
There may be a necessity to make a set-up in some regions on the edges of dipping beds that differ electrically, and if the line of electrodes is run across the strike it is possible that more than one forma-


Graph No. 5
Depth
T


Graph No. 6
Depth
T

tion is included in the circuit. In other instances the width of outcrop of a formation may be so small that the current circuit and even the potential circuit extends beyond its limits and on other formations. One would not expect the measured resistivity to be that characteristic of one formation alone.

An actual test case of this type was run by making a depth determination from a set-up at the contact of two electrically different formations, the Grassy Creek shale and the Chouteau-Burlington



limestones, shown in section below Graph No. 10. The results of the measurement are shown in curve 69, which occupies a position essentially midway between what would be expected for limestone, line *AA*, and for shale, line *BB*. In other words, the resistivity at the contact of two formations should be an average of their resistivities in proportion to the volume of each functioning as a conductor.

It is interesting to note that the increase in resistivity is not in proportion to the increase in depth at this particular station, but that it flattens out. The explanation is that as the depth of current penetration increases, the volume of shale included in the expanding circuit increases relatively at the cost of volume of limestone because of the

dip of the rocks, and the net result is the lowering of the rate of increase of total resistivity.

The circuit was also partitioned by using the auxiliary potential electrode, P_3, located at the formation contact. The data are represented by curves *N* and *S*, which show the values of the potentials on the north and south halves, respectively, of the potential circuit. They indicate nicely that the north half of the circuit is only about two-thirds as resistant as the south side, which is wholly in accord with the geology.

There is no indication of the prevailing structural condition in curve 69, and if the rocks were covered, this contact would be passed over unknowingly. A partitioned circuit, however, would give warning, at least, that the geology was changing, if not a fair indication of the nature of the components as a whole.

BEHAVIOR OF MULTIPLE ROCK SYSTEMS

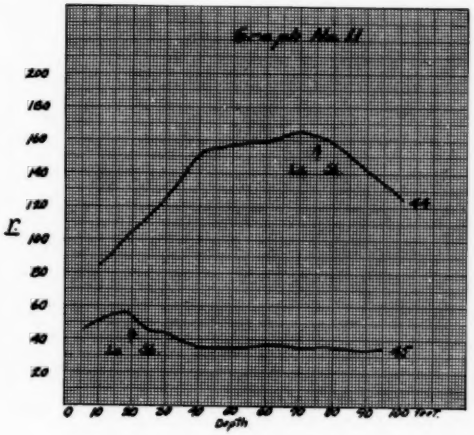
After a consideration of the resistivity of a single type rock, the next logical step is toward a system of two. Suppose that 25 feet of bed *A* underlie 75 feet of bed *B* and a depth determination is made to 100 feet. What will the resistivity figures for the 76- and 100-foot depths be? Will the 100-foot figure be the same as that for 100 feet of *B*, 100 feet of *A*, 75 feet of *B*, 25 feet of *A*, an average of 25 feet of *A* and 75 feet of *B*, or any other combination? The field answer is shown in the following paragraphs.

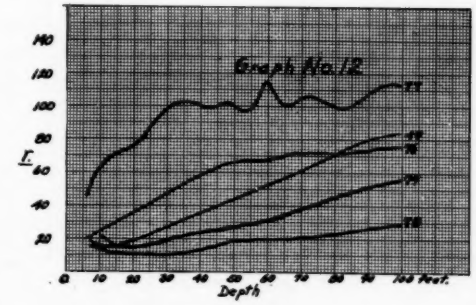
HIGH OVER LOW RESISTIVITY

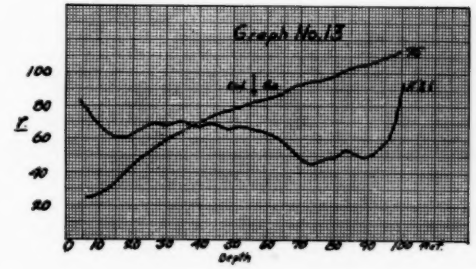
Graph No. 11 carries two resistivity curves of 20 feet and 75 feet of limestone over 80 feet and 25 feet of shale, respectively. In curve 45 the resistivity starts at 46 units and rises in a normal limestone slope to an 18-foot depth and then drops to a shale level. The electrical prediction of shale at 18 feet, that is, the break in the curve, with actual occurrence at 20 feet, is satisfactory.

In 44 the curve is typically that of limestone to a depth of 70 feet, where it falls consistently to that of shale. The electrical prediction of 70 feet is apparently 5 feet in error, but the field notes on this set-up state that the current electrodes were 3 feet below the instrument from the 100-foot mark out. Prediction is again within 2 feet of actuality.

The two curves are clearly illustrative of the fact that the break in the curve follows rather closely the change in the rocks. Instead of designating the maximum or minimum in the curve as the location of the geological change, it is often customary to split the slope on a curve


Graph No. 11
R
200
160
140
120
100
80
60
40
20
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth


Graph No. 12
R
140
120
100
80
60
40
20
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth


Graph No. 13
R
100
80
60
40
20
0 10 20 30 40 50 60 70 80 90 100 Feet
Depth

if it is steep and mark the contact of the two formations at that point. Since the slope and the apparent magnitude of break in the curve will vary with the relative scale in plotting values on the axes, the depth predictions might vary slightly if either scale is exaggerated.

The writer finds that the highly conductive (low resistivity) beds apparently exert a greater effect on the current and show a thickness greater than is actually the case. Hence, it is usually more nearly correct to favor slightly the size of the beds of high resistivity at the expense of the low. An exception to this rule of thumb is in the case of overburden of high resistivity, in which case its thickness is usually slightly less than indicated electrically.

Generalizing, where bed *A* underlies bed *B* its resistivity is neither that of normal *A* or *B* at *A*'s depth below the surface but is roughly equal to the average resistivity of the two taken in proportion to the thickness of the two involved.

Stations 44 and 45 were located half a mile west of Dameron, Missouri.

LOW OVER HIGH RESISTIVITY

The curves on Graph 12 indicate the resistivities of increasing thicknesses of shale over limestone. The series was made by setting up near the base and at points consecutively higher on the side of a gently sloping, large hill of Maquoketa shale underlain with Kimmswick limestone. Electrode lines were parallel throughout, roughly following contours.

Curve 77, made with the electrodes on bare limestone in water, is repeated for reference. The resistivity rises with increasing depth of current to about 30 feet in depth, from which depth it remains fairly constant at 100–110 units. Curve 76, also repeated, is from measurements of the limestone under 3 feet of alluvium. Notice that it almost parallels the mean of 77 but is about 40 resistivity units lower, due, no doubt, to the alluvium.

Where 10 feet of shale covers the limestone its (the shale's) higher conductivity lowers the whole curve as shown in 49. The minimum point on the curve checks the 10-foot thickness nicely.

The curve of 20 feet of shale over limestone is shown by 79. Note that the higher conductivity of the shale has lowered the resistivity of the entire remaining thickness of limestone. The agreement between the actual thickness and that indicated electrically is excellent.

A 35-foot thickness of shale over 65 feet of limestone lowered the resistivity of the whole section to that of ordinary shale, as shown in curve 78. The curve indicates limestone at a depth of 30 feet, which is

5 feet in error. The curve as a whole is very poorly diagnostic and is not satisfactory. It is given to show what can and does occur in some determinations. The writer is inclined to believe that because of the fairly low resistivity of the limestone alone, and perhaps because of the nature of the contact with the shale, whatever it is, the total resistivity is low.

A second example of low resistivity rock over high is given in curve *KXI*, Graph No. 13. The log of the hole drilled by a clay auger beneath the place of set-up is:

	Feet
Gravelly soil and clay	0–10
Diaspore and burley clay	10–60
Plastic clay and rotten rock	60–95
"Cotton rock" (Jefferson City dolomite)	95—

The transition in this case from "plastic clay and rotten rock" to dolomite is sharp and clear. The electrical prediction of dolomite at 96 feet was very satisfactory.

Perhaps the upper contact of the dolomite was nonconductive or the resistivity of the dolomite high so that the influence of the clay on the total resistivity was not marked. The writer is not able to explain adequately the difference between the transitions on the two curves.

Station *KXI* was located over a diaspore pit 1.5 miles southeast of Swiss, Gasconade County, Missouri.

The stations shown on Graph No. 12 were located one mile northwest of Elsberry, Missouri.

EQUI-RESISTIVE FORMATIONS

A complete series of 2 formational resistivity curves will include those of 2 rocks of similar resistivity. Such is shown in curve 75 on Graph No. 13, at which location 56 feet of Joachim dolomite overlies the St. Peter sandstone. Since both rocks have high resistivity no marked break in the curve would be expected and there is none. A small irregularity occurs at 60 feet and may represent the disconformable contact, or, being so slight, may simply be caused by a variation in the rock. At any rate it is too small to be used as a mark separating formations in interpreting an unknown curve.

The location was half a mile west of Corinth Church, near Foley, Missouri.

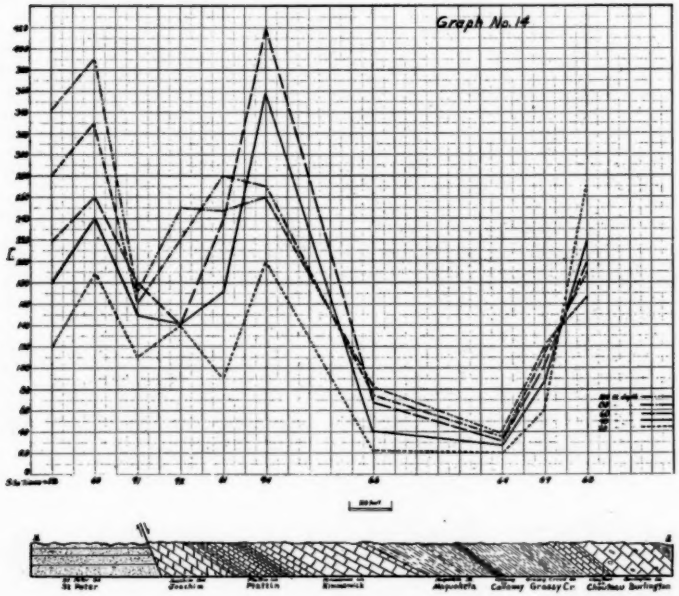
RESISTIVITIES ACROSS FAULT

In the next study measurements were made across an upturned series of rocks and an included fault occurring in Lincoln County,

Missouri. Two other applications of the earth resistivity method, traversing, and the location of a fault plane, were tested.

TRAVERSING

Stations were located along a straight line at known intervals and the resistivity of the rocks was measured at uniform depths. These resistivities were plotted against the station locations, giving a resistivity profile along the traverse. A change in the character of the



rocks was expected to show an irregularity in the resistivity profile. That such was the case is shown in the curves and cross section on Graph No. 14. Complete depth determinations were made at each station and the resistivities were plotted for 5 depths, 20, 40, 60, 80, and 100 feet.

LOCATION OF FAULT

By running traverses across a fault at three selected places a small variety of contacts were studied electrically. In one place the St. Peter sandstone was faulted against the Plattin limestone; in another, St. Peter sandstone was faulted against Maquoketa shale; and in the

third, Jefferson City dolomite was brought against Kimmswick limestone.

The geologic section of the region and a brief description of the fault are given to aid in understanding the discussion which follows.

	Feet
Alluvium	
Pleistocene glacial debris	
Pennsylvanian	
Cherokee formation	0–50
Mississippian	
St. Louis limestone	75
Keokuk-Warsaw-Salem group	140
Burlington limestone	150
Chouteau limestone	55
Grassy Creek shale	140
Devonian	
Callaway limestone	12–15
Ordovician	
Maquoketa shale	150
Kimmswick limestone	140
Plattin limestone	125
Joachim dolomite	65
St. Peter sandstone	125
Jefferson City dolomite	125

The Cap-au-Gres fault, a normal fault having a stratigraphic throw of about 450 feet in the locality worked, cuts across Mississippi River at old Cap-au-Gres, Illinois, and extends into Illinois and Missouri, trending about N. 85° W. The rocks dip away very gently north of the fault plane but are dragged up in excess of 45° on the south, the downthrown side, flattening out within half a mile. This structure brings up the greater part of the geologic section within this small area.

SANDSTONE FAULTED AGAINST DOLOMITE

Graph No. 14 carries the resistivity profiles of the measurements at 5 different depths made at the set-ups along a line across the fault where the St. Peter sandstone was faulted against the Joachim dolomite. The traverse was also continued across the greater part of the upturned geologic section.

The stations at which the determinations were made were located at fairly regular intervals along a small valley in which the soil thickness was probably as uniform as could be found. The line of electrodes was always north-south, across the strike. Most of the stations were 100 feet apart, under which conditions the 100-foot maximum spacing of the potential electrodes formed a continuous length of potential measurement. The current circuits were overlapping, of course, in those cases. At any rate, the position of the stations is plotted to scale along the abscissa. Resistivity is shown on the ordinate. The

geologic cross section along the traverse is drawn at the bottom of the graph in its proper position with respect to the ten stations.

For convenience in analyzing Graph No. 14 let us proceed along the traverse from north to south, left to right along the page.

The first stations, 58 and 60, are on the highly resistive St. Peter sandstone. There is a fairly uniform increase in resistivity with depth; the figures on the whole are high; the curves are roughly parallel; in other words, they are typical sandstone curves. The increase in resistivity of 60 over 58 is believed to be due to increased silicification near the fault plane, evidenced by the fact that the sandstone in its outcrops nearest the fault shows a little crushing and some cracks and veinlets filled with quartz and calcite.

A sharp drop in all profiles occurs at 91. The writer does not believe this to be due to low resistive Plattin limestone or Joachim dolomite, which would be taken in below at greater depth, but rather to possible clay gouge and similar material perhaps well saturated by movement of water along the plane.

Upon advancing to 92 the current is dominantly in Plattin limestone and the resistivity increases. It rises to a maximum over the center of the limestone series at 94.

The low profile over the Maquoketa and Grassy Creek shales needs no comment after one has seen their normal curves. Station 69 shows higher resistivity because the south current electrode has been extending over the Chouteau and Burlington limestone.

Further advance to 68 over limestone is indicated by a rise in the profile. This set-up is one of the most interesting made. Since the instrument was set up at approximately the center of the limestone formation, one would expect, without further analysis of the conditions, a normal increase in resistivity with depth. However, exactly the opposite is what happens. Each increasing depth shows a corresponding decrease in resistivity. But after consideration of the geology of the traverse the explanation is easily made. At a 20-foot depth the outer electrodes are separated 60 feet, still on limestone; but as the potential electrodes are separated wider the current electrode spacing is tripled, and they pass off the limestone at each side, going onto the Grassy Creek shale at the north and the intercalated shale and limestone of the Keokuk-Warsaw group at the south, whereby the resistivity is lowered. With increased spacing more shale is taken into the circuit, outweighing the limestone, and consequently the curve declined all of the way to the end.

The conclusion that a covered fault can be located by an earth resistivity method is self-evident. There is nothing original or new

in the confirmation of that fact. The writer does, however, consider that the location of the plane between the sandstone and limestone because of the low resistivity of the fault zone is worth mentioning.

Another item of importance in practical prospecting, that having to do with the determination of the optimum spacing of electrodes for rapid traversing, can be derived, tentatively at least, from this graph. For instance, when a party is doing commercial traversing or reconnoitering, the element of time and expense enters in. It would usually be too costly to make detailed determinations at each station. Instead, only one depth reading or perhaps two which are most diagnostic would be made.

A glance at the profiles of the different depths, although of the same traverse, shows that they are not the same. Their variation, however, is not such that one contradicts the other, as might be argued, but instead, if the geology involved is studied, their interpretation is entirely logical.

Inspection of the graph shows that a 20-foot depth determination is hardly satisfactory because of the relatively great influence of local variations in the soil or mantle rock. At the other extreme, a 100-foot potential electrode spacing takes in 300 feet between current electrodes, which is so large that it usually includes more rocks in the circuit than is desirable. The 80-foot depth, as shown on the graph, is not much better than that of 100 feet. The 60- and 40-foot depths appear to be almost equal in their diagnostic values, perhaps the 60-foot one being a bit more pronounced. On the other hand, if one is prospecting for small ore deposits, the 40-foot spacing would be preferred because its current circuit takes in 60 feet less of rock that might alter the effect of the ore, than does that of the 60-foot spacing. The choice of the two should really be determined by the use to which the prospecting is to be put.

The section shown on Graph No. 14 is located on the C. T. Cannon farm, 3.5 miles southwest of Foley, Missouri.

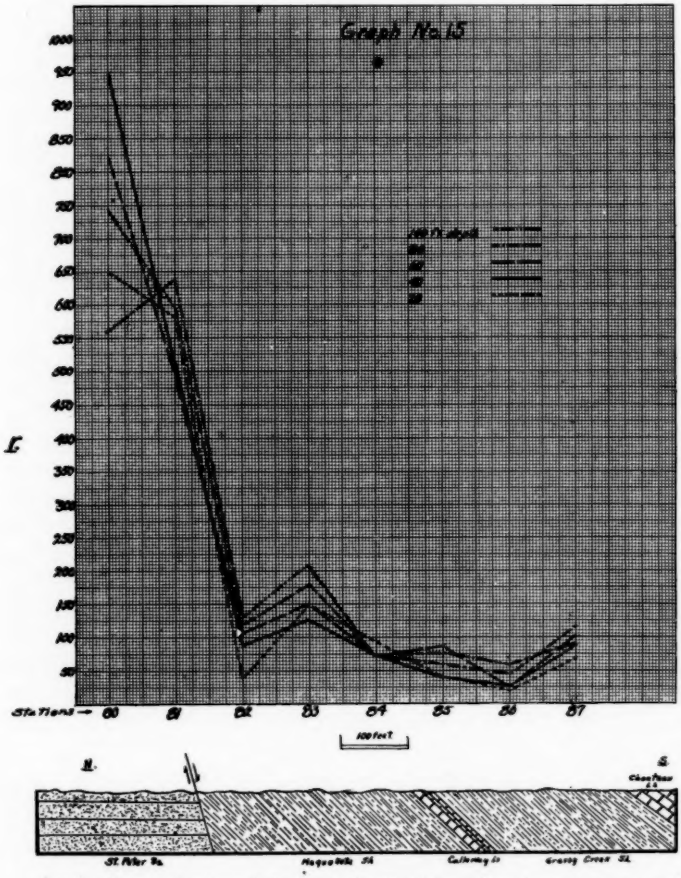
SANDSTONE FAULTED AGAINST SHALE

A fault where sandstone is brought against shale is sharply indicated by earth-resistivity methods. The curve showing the extremes of high resistivity of sandstone and adjacent low resistivity of shale has an abrupt steep slope between the two that permits ready location of the contact of the two formations.

The resistivity curves on Graph No. 15 demonstrate nicely such a fault condition found near McClain's Creek Crossing, 5 miles west

of Foley, Missouri. Determinations were made in the same manner as in Graph No. 14.

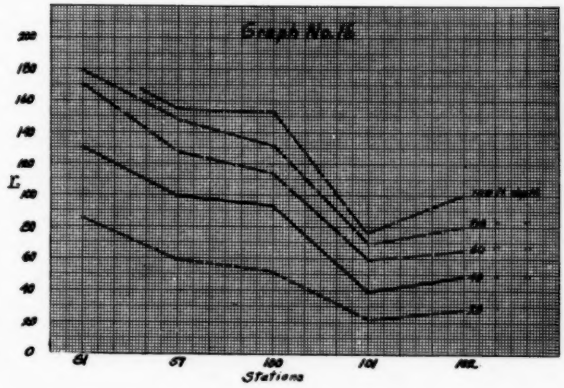
It is evident that a fault is easily detected where sandstone is faulted against shale.

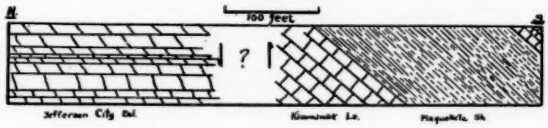


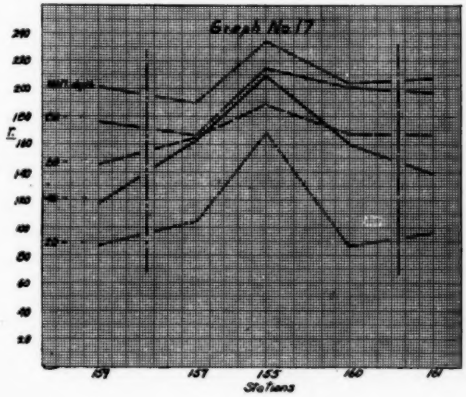
Again the 40-foot and 60-foot depth determinations appear to be most diagnostic for average changes in the rocks at a depth less than 100 feet.

DOLOMITE FAULTED AGAINST LIMESTONE

Jefferson City dolomite is faulted against Kimmswick limestone at Lick Spring Farm, 3 miles south of Foley, Missouri. Graph No. 16


Graph No. 16
Stations


100 feet
?


Graph No. 17
Stations

shows the cross section and resistivity profile along a traverse crossing the fault there. The resistivities of the dolomite and the limestone are so nearly alike that no direct indication of the fault is given by this method. There was no evidence of clay gouge in the fault plane or variation in resistivity due to mineralization. The resistivity of the rocks is of little direct value in this case.

However, if the observer keeps his geologic section in mind, he may be able to approximate the position of the fault or at least be aided in his search by the location of the Maquoketa shale. He may be aided indirectly, although given no direct evidence.

This study serves to indicate that earth resistivity methods of prospecting are no panaceas for all geologic ills but simply additional tools useful in prying loose the sometimes tightly held secrets of Mother Earth, and that to gain most information from the electrical data of the rocks their geological relations must ever be kept in view.

A consideration of the three resistivity profiles across the fault plane leads to the following conclusions.

1. The mere presence of a fault plane does not necessarily cause a break in the resistivity profile. The resistivity at the plane is not necessarily a convenient and opportune variation from those of its flanks, regardless of what their values may be.

2. However, the location of the position of a fault plane is to be expected more usually as a result of fundamental differences in the resistivity of the two adjoining formations.

ALNOITE PIPE IN DOLOMITE

The writer's study of the resistivity of igneous rocks was too brief to be conclusive, as has been said before, but one set of curves, taken where an alnoite pipe is intruded into dolomite, is believed to be significant enough to be included because of the possible application to the location of intrusives into sediments. The pipe described by Singewald and Milton[5] is exposed for about 120 feet in length and 15 feet in width. It occurs in a small ravine eroded in a wide, gently sloping hillside which affords an excellent surface for earth resistivity tests.

The traverse was run from the dolomite on one side, across the pipe, and onto the dolomite on the other side. The line of electrodes was run in a north-south line which was fairly level and in a direction transverse to the long axis of the outcrop.

[5] Joseph T. Singewald, Jr., and Charles Milton, "An Alnoite Pipe, Its Contact Phenomena, and Ore Deposition Near Avon, Missouri," *Jour. Geol.*, Vol. 38 (1930), pp. 54–66.

Graph No. 17 carries the resistivity profiles along with the probable section sketched below it. Curve 159, which was taken on the north end of the traverse, 600 feet north of the pipe, is a normal dolomite curve. After advancing to 157 we find the resistivity to rise rapidly at lower levels and then flatten. Apparently a highly resistive body lies at the south.

Station 155 is directly over the pipe. Its entire resistivity determination, and particularly that for the 40-foot depth, is somewhat higher than that for the dolomite. Apparently alnoite is more resistive than dolomite.

Normal dolomite resistivities are resumed by moving over 160 and 161.

It is questionable whether the earth-resistivity method could be relied on to locate similar pipes or dikes in a similar dolomite. The increase in resistivity over this pipe is relatively small, and that amount of variation can be caused as well by such other factors as variations in soil and topography. In this case, however, there is hardly any doubt that the rise in resistivity is due to the igneous rock. If no other evidence of the existence of an intrusion had been at hand, the profile on Graph No. 17 would probably not have been interpreted as it has been.

However, the method could be used to supplement core drilling or to follow buried dikes from their exposures.

In view of the resistivity values obtained from these set-ups there is hardly any doubt that intrusions in shales could be detected readily.

CONCLUSIONS

The data obtained by the writer, using a modified Gish-Rooney earth-resistivity apparatus while working at depths less than 100 feet, lead to the following conclusions.

1. Damp alluvial and residual soil, shale, clay, and other argillaceous materials show a relatively low resistivity.

2. Gravelly deposits and soil, sandstone, limestone, and igneous rocks show a high resistivity.

3. The same formation shows a higher resistivity where located in a well drained place than where saturated with water.

4. The resistivity of a formation taken through an overlying one is roughly equal to an average of the resistivities of the two in the proportion to their thicknesses involved in the test.

5. If both current electrodes or potential electrodes are not set in the same formation, or if a foreign body lies between the electrodes,

the portions of the circuits on each side of the observer will be unsymmetrical or unequal electrically. The difference between the two is measured by connecting in a centrally located supplementary potential electrode placed at the instrument. This partitioning operation is important in prospecting where lateral changes in the rocks are significant or critical.

6. When rapid traversing is being done in search for deposits or lateral changes at depths less than 100 feet, an electrode spacing of 40 feet or 60 feet seems to be the optimum.

7. The location of a bed, deposit, structural change, or water table is due primarily to differences in inherent resistivity of the bodies rather than to a difference induced by the transition surface of the bodies or conditions. Hence, it is difficult to differentiate between two unlike adjacent bodies having a similar resistivity.

8. The routine of making measurements and obtaining resistivity data is the lesser part of the work of the resistivity prospector. The logical and proper interpretation of the resistivity "code" is by far the greater thought-provoking part of his task. For a most efficient and successful prosecution of the method, the observer should correlate the resistivities, so far as possible, as they are obtained in the field with the changes in topography, soil, water table, and probable changes in geology. For that reason, data which are obtained by an untrained observer in "cookbook" fashion can not be interpreted in the office to their fullest extent. It is likewise most essential that the observer have an understanding of the fundamentals of geology.

9. The earth-resistivity method can probably not be advantageously employed by one going into an area in which the geology is entirely unknown. It will probably find its greatest value in supplementing and filling gaps between core-drill prospects, locating the position of hidden structural changes thought or known to exist in the area, and rapidly, approximately, and cheaply determining depths and thicknesses of strata, particularly overburden over solid rock, and in use in some types of rapid reconnaissance work.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 63-68, 3 FIGS

RADIOACTIVITY OF SOIL GASES[1]

LYNN G. HOWELL[2]
Houston, Texas

ABSTRACT

The X-ray activity of the radon in the gases drawn from the soil was measured by means of a Wulf-type electroscope having a 10-liter ionization chamber. The method of making the measurements is described. Indications that a fair sample of gases was obtained at a station were found by repeating measurements at the station on separate days. However, there are some conditions under which repeated measurements may not check. A typical line survey in the Gulf Coast region shows large variations in radioactivity of the gases in the soil. Similar variations are found in a faulted region where there seems to be little hope of correlating the positions of high radioactivity with the positions of the faults; this agrees with the work of Botset and Weaver.

INTRODUCTION

Radioactive minerals are found distributed throughout the upper crust of the earth and are thought to be concentrated for the most part in a limited layer (1)[3] of the order of tens of kilometers in thickness. Due to the presence of these minerals in the earth, a knowledge of the processes of radioactivity has been of great value in geophysics, especially in connection with the accounting for the generation of heat in the earth and with calculations of the ages of the various layers in the earth's crust.

In applied geophysics the properties of radioactive minerals have been of importance mainly in the location of the radioactive ores themselves. However, Ambronn (2), Link and Schober (3), and Mueller (4) have made surveys of the content of radon in the soil gases over subsurface features of the type represented by faults, in the close neighborhood of which an increase in radon content was found. Bogojavlensky (5) has made surveys of the intensity of penetrating rays coming from the radioactive minerals in the top layer of the earth and has reported finding radiations many times more penetrating than the known radiations from radioactive substances. These results can hardly be considered as well established. Bogojavlensky (6) has also claimed to have found an increase in intensity over pools of oil in

[1] Read before the Geophysics Division of the Association at the Houston meeting, March 24, 1933.

[2] Geophysics research department, Humble Oil and Refining Company. Introduced by L. W. Blau.

[3] Parenthetical numbers refer to Bibliography at end of this article.

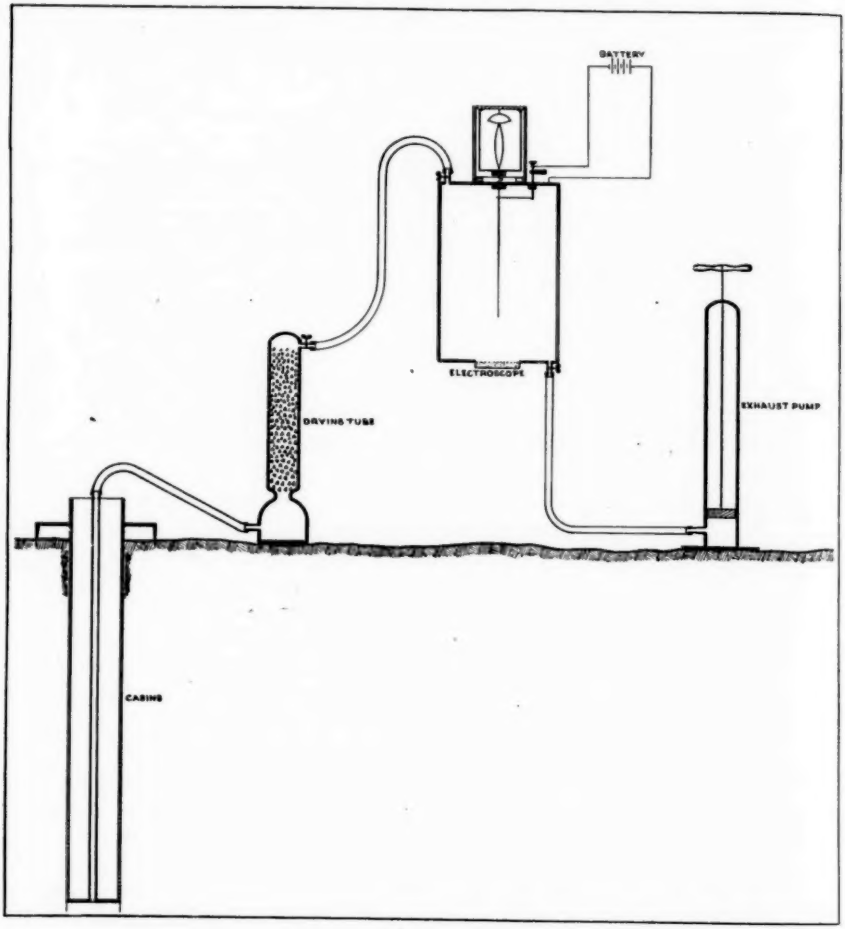


FIG. 1.—Apparatus for making relative measurements of radon content of soil gases.

one or two cases. This result can have little practical application in the direct location of oil. Practically all of the radiations from radioactive substances are absorbed by a few feet of soil and since oil usually occurs hundreds of feet below the surface of the earth, the radioactive minerals associated with oil are in practice much too deep to be detected.

EXPERIMENTAL

For the purpose of making relative measurements of the radon content of the soil gases, an apparatus resmbling that of Elster and Geitel (7) was constructed as is shown in Figure 1. The gases are drawn out from a hole in the soil about 5 feet deep through the inside tube of a 3.5-inch iron casing driven into the hole. The circular flange at the top of the casing driven into the ground helps to give a better seal at the surface of the ground. The gases are passed through calcium chloride drying tubes into the 10-liter ionization chamber of the electroscope which contains a phosphorus pentoxide drying dish. The gases are pulled through the system by a suction pump.

The electroscope for measuring the X-ray activity of the gases is of the Wulf type. In the upper chamber, the platinized quartz fibers, whose deflection is read with a reading microscope, are suspended at the top from an insulating quartz fiber bow. The fiber system is insulated from the case at the lower end by means of an amber plug. The air in the upper chamber is dried with phosphorus pentoxide. The fiber system is connected to the rod electrode in the lower chamber, the rod being held in an insulating ambroid plug. The charging lever is shown at the top of the ionization chamber on the right. A bank of a dozen small 22.5-volt B batteries is used as a source of charging potential.

Although the Elster and Geitel method of filling the ionization chamber would not seem to be as satisfactory as the later method used by Ambronn (8), since there is a possibility that the original air in the chamber may not be completely pumped out and the quantity of this air remaining may vary with each filling of the chamber, still the consistency of the results obtained by repeating measurements with gases from different holes at a given point would seem to indicate that the method was reliable enough for this type of measurement, in which consistency of repeated readings rather than precision of any particular reading seems desirable.

The Wulf-type electroscope is quite suitable for field work in spite of the fact that it has a delicate suspension. This suspension will stand rather severe jars and the calibration remains essentially con-

stant with time. The sensitivity is such that the readings can usually be taken over time intervals sufficiently short so that the temperature changes are too slight to change appreciably the deflections of the fibers by expansion or contraction of the frame holding the fibers.

In the field procedure, readings taken with a stop-watch, of the discharge of the fibers, usually over a range of four divisions on a 100-division scale in the eye-piece, are begun immediately after the soil gas is sucked into the chamber from a hole bored in the ground with an augur. The pumping is usually maintained uniform by making a given number of strokes of the pump. These readings are repeated until a fairly constant value is found. The thoron in the soil gases at some points causes a more rapid discharge in the beginning, but since it decays very rapidly with a half-life of 54.5 seconds, its effect is soon negligible. There is, of course, an increase in activity while the active deposit is coming into equilibrium with the radon, but this increase is fairly slow after a short time.

RESULTS

As an example of consistency which could be obtained under favorable conditions, the following data are presented which show the rates of discharge at one station on different days.

Date	*Rate of Discharge Divisions per Second*
Dec. 8	.22
Dec. 21	.12
Dec. 23	.13
Dec. 29	.11
Dec. 31	.11
....	.17

The first five readings were taken with gas taken from different holes spaced along a line with an interval between holes of the order of 4 feet. Even the discrepancy between the two extreme readings is not serious, since in a field survey, a "radioactive low" reading is of an entirely different order of magnitude from a "radioactive high" reading.

The following data were obtained in another area at several different stations, the interval between stations in general varying from about 200 to 1,500 feet. The readings at these stations were repeated after the capacity, and hence the sensitivity, of the electroscope had been changed. A new hole was drilled at each station within a few feet of the original hole for these check readings which were made several days after the first readings.

Station	*First Reading (Time of Discharge of 4 Scale Divisions)*	*Second Reading After Change of Sensitivity (Time of Discharge of 4 Scale Divisions)*
A	10 Sec.	24 Sec.
B	3·5	8·5
C	2	3·5
D	(Very wet hole)	>40
D	3·4	10
E	21	50
F	6	13
G	45	85

The check is very good (the ratio between readings being of the order of 2), especially since the error in measuring some of the shortest time intervals is appreciable.

However, consistent results are not always obtained. For example, in dry cracked ground the readings are increased after a rain has closed up the cracks. After a rain not only is there a possibility that a better seal can be obtained around the casing and that the gases in the ground can not diffuse into the atmosphere so freely, but also, as is well known, dry radioactive salts tend to retain the radon produced by their decay. The radon can be released by dissolving the radio-

FIG. 2.—Typical line survey in Gulf Coast region.

active salts, and thus it may be that radon is set free in dry ground after a rain by this process of dissolving dry radioactive salts. However, if the ground becomes too wet, it becomes difficult to extract gas as the ground pores are filled with water for the most part. There are a number of factors which influence the radon content of the soil gases, and since these have been discussed at length by others, it seems hardly worth while to discuss them further.

A typical line survey of the Gulf Coast region is seen in Figure 2, in which the rate of discharge of the electroscope in divisions per second is plotted in the ordinate direction and the distance in miles is plotted in the abscissa direction. It will be seen that the radon content of the soil gases varies in a rather erratic fashion from point to point even though there is no apparent change in soil, except of a local nature. The curves in Figure 3 represent two line surveys in a

faulted region. The positions of the supposed faults are shown beneath the curves. It is readily seen that any sort of correlation is difficult. The distribution seems erratic, as in the case of the previous curve for a supposedly non-faulted region. This lack of correlation between faults and radioactive "highs" is in agreement with the work of Botset and Weaver (9), who also worked in Texas. Along a line in one region, Clark and Botset (10) found a rather close correlation between the radon and the heavy mineral content of the soil.

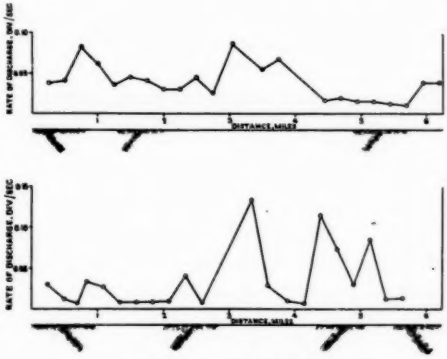


FIG. 3.—Line surveys in faulted area.

Although it is possible that the methods of radioactivity may be of some value in the study of local soil variations, at the present stage of our knowledge there seems to be little application for these methods in petroleum geophysics, at least in the Gulf Coast region.

In the work reported herewith the observations in the field were taken by Bruce Hill under the direction of L. W. Blau.

BIBLIOGRAPHY

1. Harold Jeffreys, *The Earth*, Macmillan (1929), p. 144.
2. Richard Ambronn, *Elements of Geophysics*, translated by Margaret C. Cobb, McGraw-Hill (1928), p. 127.
3. E. Link and R. Schober, *Gas and Wasserfach*, Vol. 69 (1926), p. 225.
4. Ferdinand Mueller, Radioaktivitätsmessungen als geophysikalische Aufschlussmethode, *Zeits. f. Geophysik*, Vol. 3 (1927), p. 330.
5. L. N. Bogojavlensky and A. A. Lomakin, "Experiments on Highly Penetrating Radiations from the Earth," *U. S. Bur. Mines Cir. 6072* (1928).
6. L. N. Bogojavlensky, "Radiometric Exploration of Oil Deposits," *U. S. Bur. Mines Cir. 6072* (1928).
7. J. Elster and H. Geitel, *Physik. Zeits.*, Vol. 3 (1902), p. 574.
8. Richard Ambronn, *Elements of Geophysics*, translated by Margaret C. Cobb, McGraw-Hill (1928), p. 118.
9. Holbrook G. Botset and Paul Weaver, *Physics*, Vol. 2 (1932), p. 376.
10. R. W. Clark and Holbrook G. Botset, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 12 (December, 1932), pp. 1349–56.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 69-96, 11 FIGS.

MAGNETIC AND TORSION-BALANCE SURVEY OF MUNICH TERTIARY BASIN, BAVARIA[1]

DONALD C. BARTON[2]
Houston, Texas

ABSTRACT

The Munich Tertiary basin consists of a structural basin of Tertiary sediments. It is bounded on the east by the Bohemian crystalline massif; on the north by Mesozoic sediments which dip southward under it; and on the south, it has been overridden by the Alpine overthrusts. The whole Bavarian part of the basin has been covered by a close net of lines of observation of the vertical component of magnetism. Two torsion-balance lines were run north-south across the basin, and some additional cross lines were run. The geophysical survey indicates: (1) the surface of the crystalline basement dips southwestward across under the Tertiary basin; (2) the Bohemian crystalline massif seems to dip under the Austrian continuation of the Tertiary basin, to connect with the crystalline core of the Austrian Alps; (3) the Bohemian massif seems to have a sharp subsurface scarp on the southward prolongation of the Regensburg fault; (4) the basement under the Tertiary sediments is not the crystalline basement, but presumably the surface of a wedge of Mesozoic rocks; (5) the crystalline core of the Vendelician ridge must be south of the present Munich Tertiary basin; (6) a line of hitherto unsurmised structures with basaltic cores lies along the Danube from Vohburg to Ulm; (7) the cause of most of the residual magnetic anomalies is not clear, but the Passau axis of the maximum seems to reflect structure with the basement; (8) no folding is indicated parallel with the front of the Alps.

INTRODUCTION

This paper presents the more broadly interesting results of an extensive magnetic survey and a less extensive torsion-balance survey which were made of the Munich Tertiary basin by the Bayerische Mineral Industrie A. G. in the search for possibly petroliferous structure. The execution of the surveys was under the immediate supervision of E. Gundermann. The field torsion-balance observations of the reconnaissance traverses were made under contract by "Seismos" Gesell.G.m.b.H. of Hannover. The field magnetic observations were made by O. Keunecke, G. Meyer, and W. Wolff, and G. Sander under the supervision of Gundermann. General direction from a distance and interpretation of the results of the geophysical surveys were by the writer. The whole program of the Bayerische Mineral Industrie was under the direct supervision of J. Elmer Thomas.

[1] Read before the Geophysics Division of the Association at the Houston meeting, March 24, 1933. Part of this paper was read before the XVI International Geological Congress at Washington, D. C., July, 1933. Published by permission of J. Elmer Thomas, Bayerische Mineral Industrie A. G. A more detailed description of the survey and more extensive discussion of the results is to be published by the *Geologische Abteilung*, Bergamt, Bayern.

[2] Consulting geologist and geophysicist, Petroleum Building.

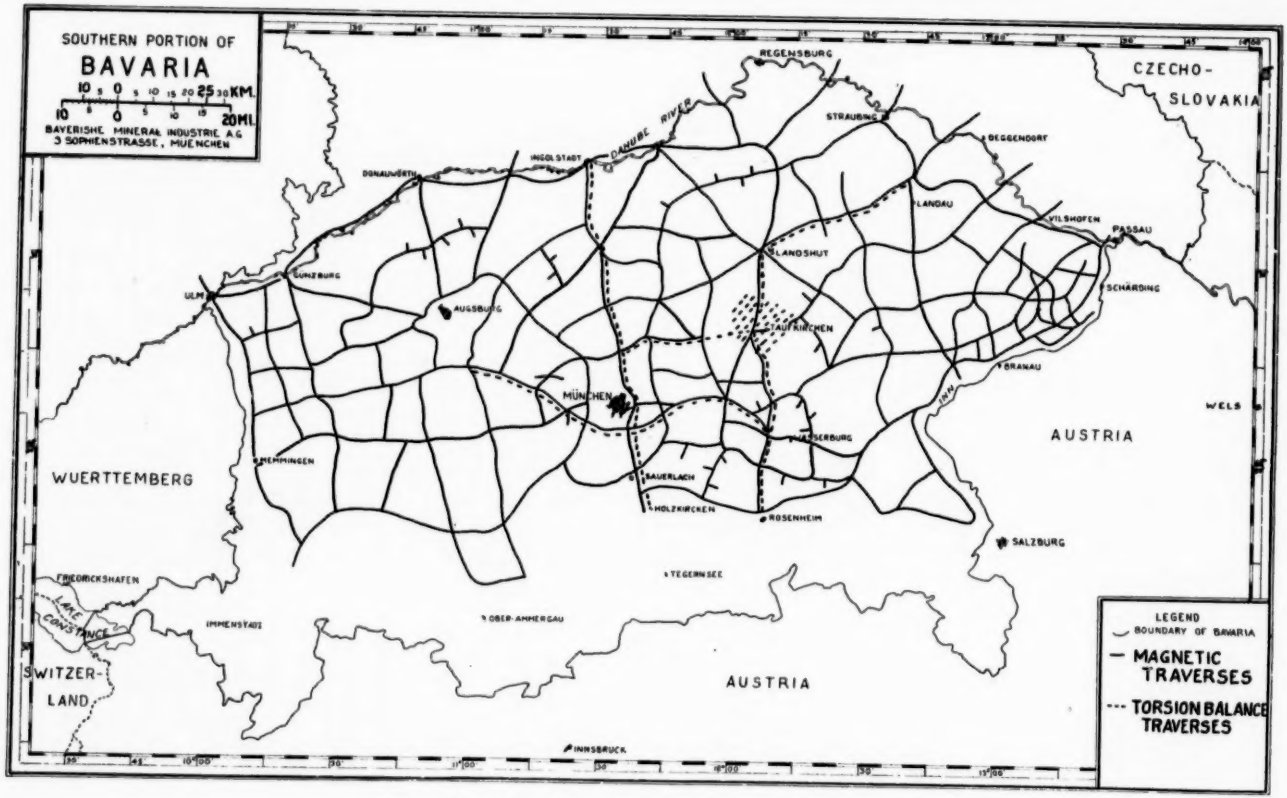


FIG. 1.—Map of B. M. I. magnetic and torsion-balance traverses.

The torsion-balance survey (Fig. 1) comprised 1,195 reconnaissance stations and 366 detail stations. The reconnaissance stations are disposed: (1) in two north-south lines, one from the Danube at Ingolstadt to the edge of the foothills at Holzkirchen, and the other from Landshut to the foothills at Rosenheim; and (2) in a composite east-west line through the central part of the basin. A station interval of 200 meters was used on the Ingolstadt-Holzkirchen traverse in order to detect structures with narrow anomalies as well as structures with large anomalies and to determine the degree of surface irregularity of density. The station interval subsequently was increased to 400 and 600 meters. A latitude correction of 8E was used in the routine calculation of the gradient. The gradient effect of the Alps was neglected; the gradient which is produced at Sauerlach by the topographic mass of the Alps was calculated to be $+1.4$ for U_{zz}; as that gradient varies slowly and smoothly and is small compared with the observed gradient, it need not be eliminated unless quantitative calculations of structural profiles are made or unless the position of structures near the foot of the mountains needs to be determined with high accuracy.

The magnetic survey (Fig. 1) comprised 14,743 stations with a Schmidt-Lloyd vertical variometer. Those stations are disposed in a criss-cross series of reconnaissance traverses which covered thoroughly the whole of the Munich Tertiary basin and which extended into the foothills of the Alps on the south, and across the Danube into the Frankish-Schwabian Jura on the north, and the area of the Bohemian massif on the northeast. A primary base line of magnetic benchmarks was run between Ingolstadt and Holzkirchen; the value of Δz was determined by rapid runs in an automobile between benchmarks until a consistent series of determinations was obtained; from that base line, a net of primary benchmarks was similarly established through the rest of the area. The traverse lines were adjusted to those primary benchmarks and to each other. A station interval of 200–300 meters was used on most of the traverses. Careful checking back and careful checking in on base stations and benchmarks was practiced. Corrections were applied for the fluctuations of the intensity of the earth's magnetic field as observed at Pottsdam. The following correction for the normal increase of intensity with magnetic latitude was applied in a routine manner in the station calculations: $+8\gamma$ per 1 minute of increase of (astronomic) latitude and -1.5γ per 1 minute of increase of longitude. The magnetic survey was run as an inexpensive and rapid method of possibly supplementing the slower and more costly torsion-balance survey. The expectations of it were not great.

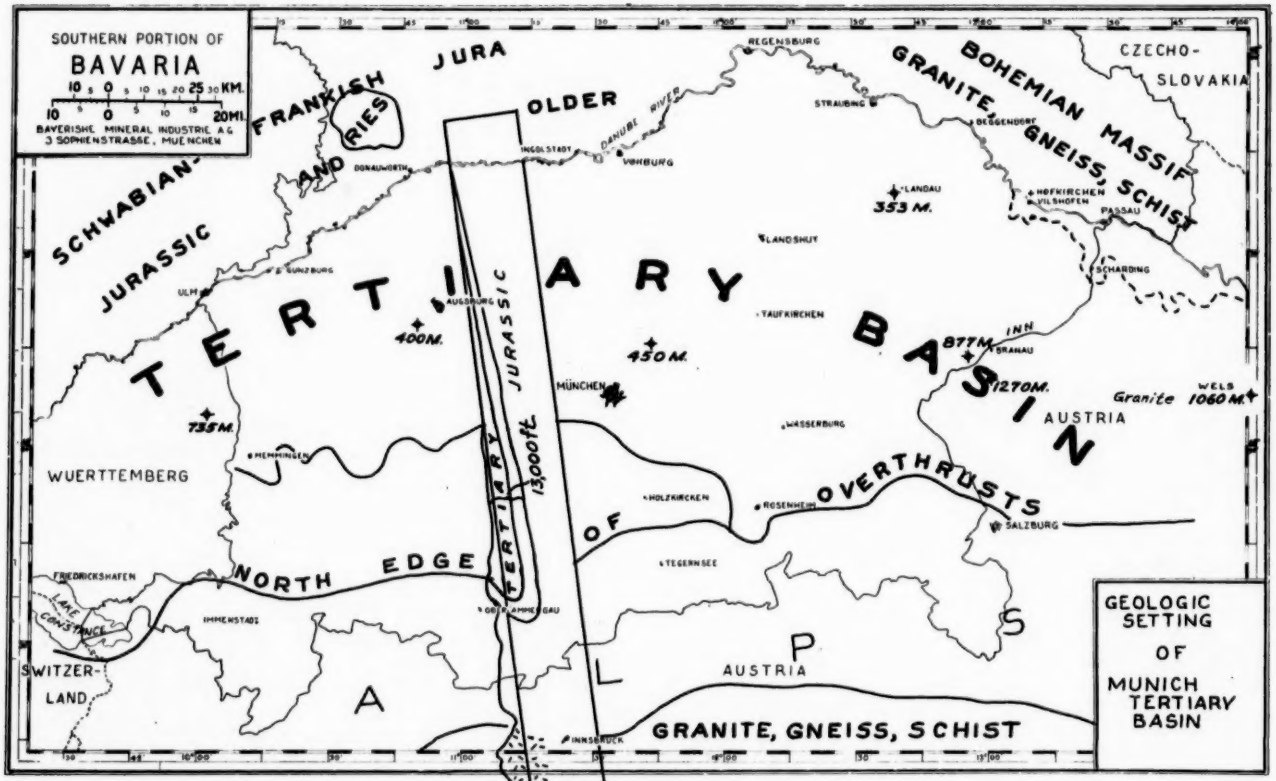


FIG. 2.—Sketch map of geologic setting of Munich basin.

FIG. 2.—Sketch map of geologic setting of Munich basin.

GEOLOGICAL SETTING

The Munich Tertiary basin of southern Bavaria is a local widening of the belt of Tertiary formations which lies in front of the northern edge of the Alpine mountain system and which extends from western Switzerland through northern Switzerland, southern Wuerttemberg, southern Bavaria, into Austria, to connect with the Vienna Tertiary basin (Fig. 2).

North of the Munich Tertiary basin, there is the broad east-northeast-west-southwest zone of the Schwabian and Frankish Jura, an area of gently dipping Jurassic sedimentary beds. The dip in general is southerly, toward the basin, although at the eastern end of the zone, the Upper Jurassic beds dip gently eastward under a thin cover of Cretaceous, and into the syncline which extends northward from Regensburg. The Malm (Upper Jurassic) and under it, the Middle and Lower Jurassic and the Triassic formations, dip under the Tertiary beds of the Tertiary basin, but the southward extent of the several members of the Mesozoic under the Tertiary basin is unknown from geologic data. The Mesozoic beds of corresponding age which crop out in the Alps are of different aspect and were deposited in an ocean basin which had no connection with the basin in which the Mesozoic sediments of Germany were deposited; and a Mesozoic landmass must have separated the two ocean basins. That ancient Mesozoic landmass has been termed the Vindelician ridge. The Mesozoic formations which dip southward under the Tertiary beds, somewhere at the south must wedge out against the north flank of the ridge. The Tertiary beds in general transgress northward over the Mesozoic formations; in the east, probably over Cretaceous; but farther west over the Malm (Upper Jurassic). At the surface, from Vohburg west to Ulm, however, the Tertiary and Jurassic beds are presumed to be in fault contact.

The Jurassic and Triassic formations are composed of well consolidated, or fairly well consolidated beds presumably of high density. The Jurassic-Triassic stratigraphic section in order of increasing age and depth has the following character: Malm, massive limestone and dolomite; Dogger and Lias, shale, marl, limestone, and sandstone; Keuper, shale, marl, sandstone; Muschelkalk, massive limestone and anhydrite; Buntsandstein, massive sandstone.

The famous Ries area lies in the zone of the Frankish-Schwabian Jura. It is supposed to be the result of an enormous volcanic explosion; and in the general area around the Ries, the Jurassic beds have been cut by a considerable number of igneous intrusions.

On the east-northeast side of the basin, there is the Bohemian crystalline massif composed of granite, gneiss, and schist. From Regensburg to Hofkirchen the Tertiary beds are in fault contact with the crystalline rocks. But farther south, in the Passau district, the Tertiary beds are at least partly transgressive over the crystalline rocks and over a few small remnants of Jurassic; and there certainly is no fault contact between the Tertiary beds and the crystallines comparable with that between Regensburg and Hofkirchen. The Danube flows on the contact between the Tertiary beds and the crystallines from Regensburg to Hofkirchen; and across the crystallines from Hofkirchen to Passau.

On the south, the Tertiary basin is overthrust by the Alps, whose northward driven overthrusts have overridden the southern part of the basin; how far, is a question; and the Tertiary beds of its southern edge, and underlying Cretaceous beds, have been turned up on end.

Gumbel's Vindelician ridge, or divide of dry land, is supposed to have come into existence at the beginning of the Triassic, and, according to Beyschlag, to have continued in existence throughout the Mesozoic and into the beginning of the Tertiary. It is presumed to have extended from the Bohemian massif through the Swiss-Upper Bavarian upland area to the Plateau Centrale of France.

The thickness of the Tertiary sediments in the Munich basin is unknown from geologic data. The granite was reached at a depth of 1,060 meters in a test well at Wels in Austria. The deepest (Eisenhub) well, in Austria, south of Braunau and not far from the Bavarian border, went to a depth of 1,250 meters and stopped in the Oligocene. The Ochsenhausen well in Wuerttemberg, not far from the Bavarian border, went to a depth of 738 meters and stopped in the Upper Oligocene. The deepest wells in the Bavarian part of the basin are the Juhlbach wells west of Braunau, the deepest of which went to a depth of 877 meters. The next deepest wells (other than the other Juhlbach wells) had depths only of 430, 400, 353 meters.

MAGNETIC AND GRAVITY QUANTITIES REPORTED

The magnetic and gravity quantities which are reported in this paper are what may be called the "structural" variation of the vertical component Z of the terrestrial magnetic field and the "structural" variation of gravity.

The results of observations of such quantities as the intensity of Z or of gravity can be reported in various ways. In geodetic surveys the value of gravity commonly is given (1) as the observed value at the station, (2) corrected for topography and reduced to sea-level

by one or more different formulae; (3) corrected also for isostatic compensation. In geodetic surveys, the absolute value of Z is reported for the date of the observation or it may be corrected to some standard date. The value of gravity varies with astronomic latitude and the value of Z with magnetic latitude. In geodetic work, commonly no correction is made for variation with latitude. A variation of gravity which can be calculated from the results of torsion-balance surveys is the variation of gravity at any equipotential surface, that is, level surface which lies approximately at the general elevation of the surface of the area, for (1) the horizontal gradient of gravity, which the torsion-balance measures, varies slowly with elevation and (2) torsion-balance surveys are made only in areas of slight relief. That variation of gravity would be comparable with the variation of geodetic observed values of gravity reduced by the "free air" reduction to a common elevation essentially that of the surface. Torsion-balance surveys such as those of the B.M.I. are made in search of structure; the effect of the variation of gravity with latitude ranges from 6 to 8 Eötvös units[3] in temperate latitudes and therefore seriously obscures the very many structural anomalies whose maximum gradient may range only from 7 to 15 Eötvös units. The effect of the latitudinal variation of gravity, therefore, is eliminated in the station calculations of the gradient. Relative gravity which is calculated from torsion-balance observations, therefore, is not directly comparable with any of the various types of values of gravity which are given in geodetic reports. The vertical component Z of the earth's magnetic field similarly varies with magnetic latitude; the latitudinal variation obscures the structural anomalies and therefore is eliminated in the routine of the station calculations in most magnetic surveys by oil companies. The observed variation of Z_s of such surveys, therefore, is not directly comparable with the variation of Z in geodetic magnetic surveys.

The observed variation of gravity (Δg_s) of this paper, therefore, is the horizontal variation of gravity at a common level, which is any level between 300 and 500 meters elevation above sea-level,—corrected for topography and for the variation with latitude. If the earth's crust and interior were perfectly homogeneous, no variation of gravity would be observed. Any inhomogeneity in the earth's interior could produce faint large-scale anomalies. The variation of density in the earth's crust and, mostly, in the upper kilometers of the earth's crust produces most of the observed anomalies of this paper and of surveys similar to the B.M.I. torsion-balance survey.

[3] 6 to 8×10^{-9} C.G.S. units per horizontal centimeter.

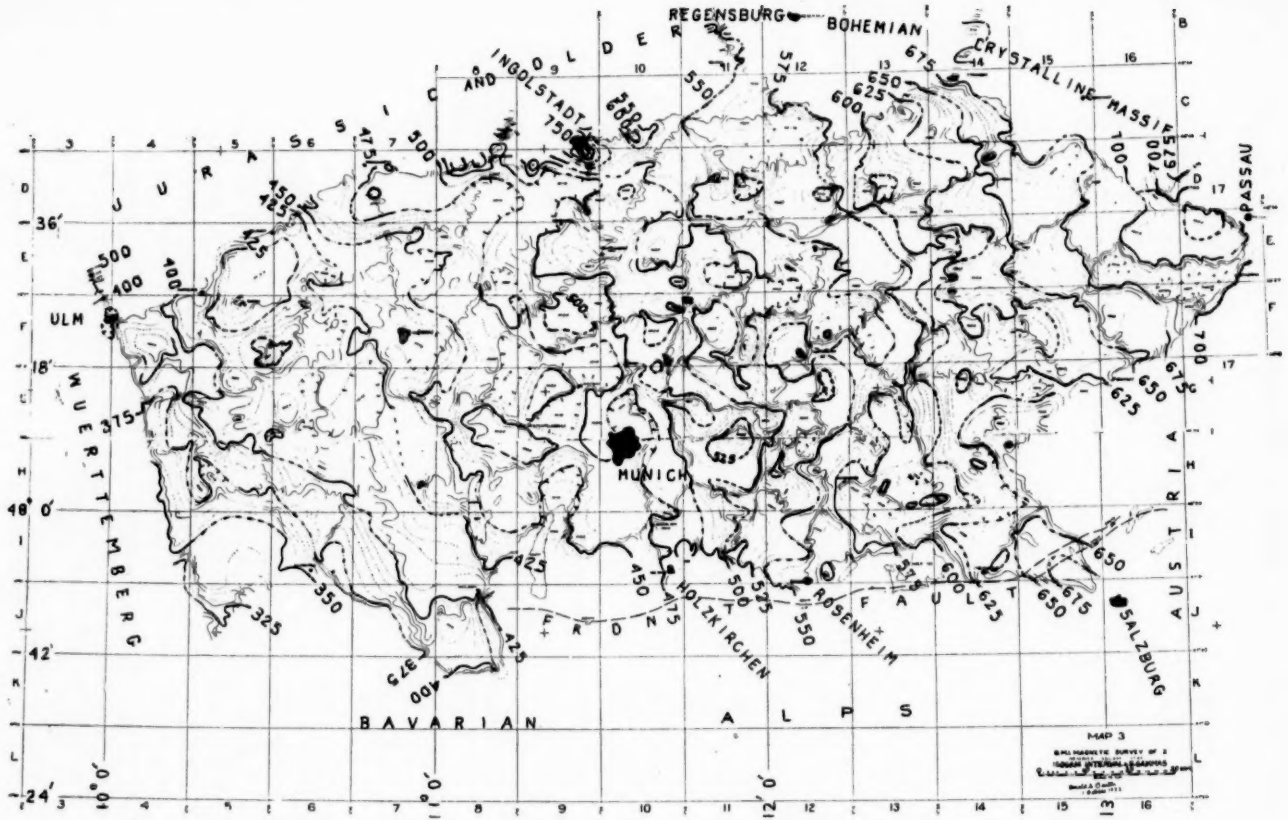


FIG. 3.—Observed variation of Δz_v, vertical component of terrestrial magnetic field. Isogam interval, 5 gammas.

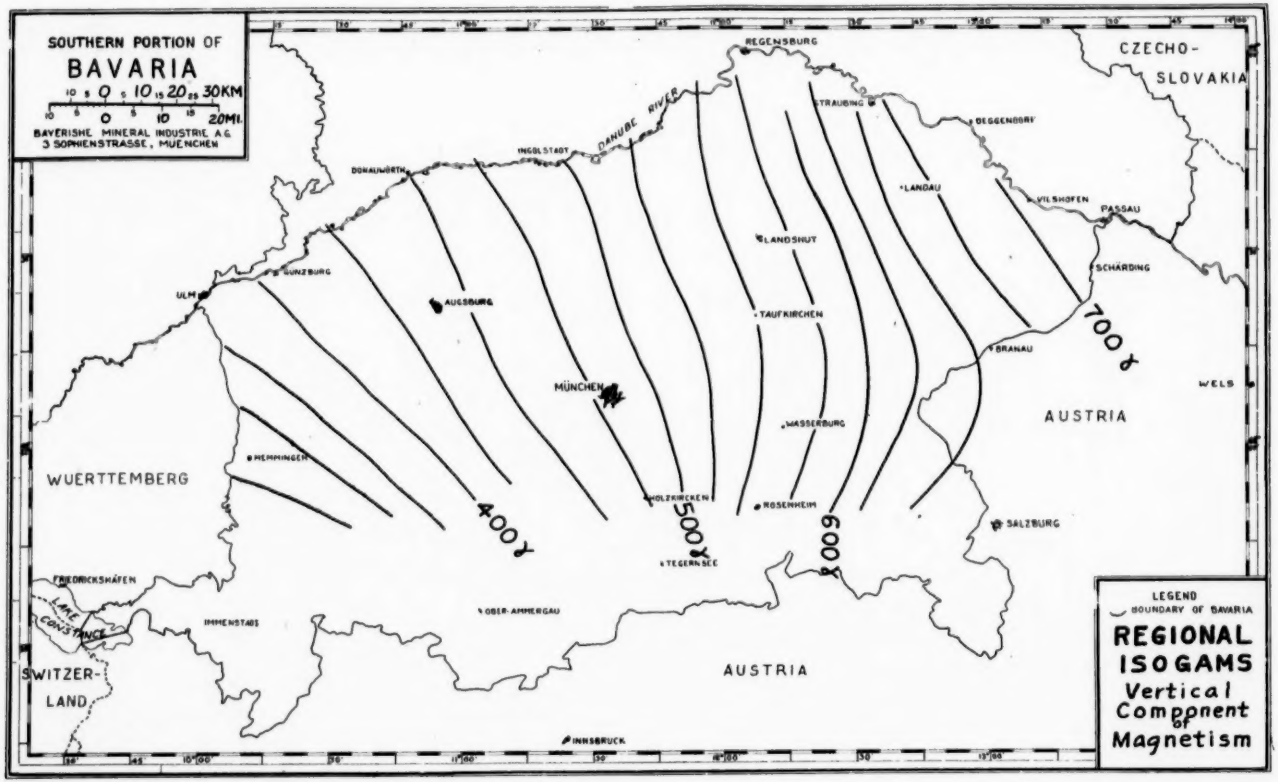


FIG. 4.—Regional variation of Δz_a.

The observed variation of Z_s, the vertical component of the earth's magnetic field, in this report gives the horizontal variation of Z corrected for latitudinal variation and as of the time when the first observation was made at the primary base station. The observed variation of Z_s is the effect of the variation of magnetic permeability in the earth's crust, and mostly of the upper 10 kilometers.

The numerical values of Δg and Δz of this paper are not absolute values, but are relative to some convenient arbitrarily chosen value at some base station.

The absolute value of gravity along the torsion-balance traverses can be calculated from the observed values of relative gravity of this paper (Fig. 5) by re-introducing the latitudinal effect and by tying those recorrected values to the known value of absolute gravity at Munich. To obtain the value of gravity at the surface, a correction for elevation would also have to be applied.

The absolute value of Z along the magnetic traverses can be calculated from the observed values of this paper (Fig. 3) by re-introducing the latitudinal effect and by tying those recorrected values to the known value of absolute Z, wherever known within the area.

REGIONAL VARIATION OF Z_s AND OF GRAVITY (g_s)

The regional variation of the vertical component of Z_s, the vertical component of the earth's magnetic field, is shown in Figure 4. The observed magnetic isogams are shown in Figure 3. The complex irregularity of their winding obscures their regional pattern. In Figure 4, the 25 isogams have been smoothed out without regard to local anomalies. The smoothing is not difficult over most of the area; but from Ingolstadt westward along the Danube, the large local anomalies obscure the regional picture; and for the area from Ingolstadt west, it is a question whether the northern ends of the regional isogams should not show a curvature westward.

The following characteristics of those isogams should be noticed: (1) their trend in general is north-northwest and south-southeast, approximately parallel with the southwest edge of the Bohemian massif; (2) they curve toward the southwest in the southeastern part of the area, in front of Salzburg; (3) the spacing between the 575, 600, and 625 isogams in the north half of their course is closer than normal; (4) the isogams in the southwest part of the area tend to ray into a west-northwest trend; (5) the failure of the northern ends of the 325–525 isogams to begin to curve westward is not necessarily significant, as the large local anomalies and the lack of data on the north obscure the pattern of the regional isogams.

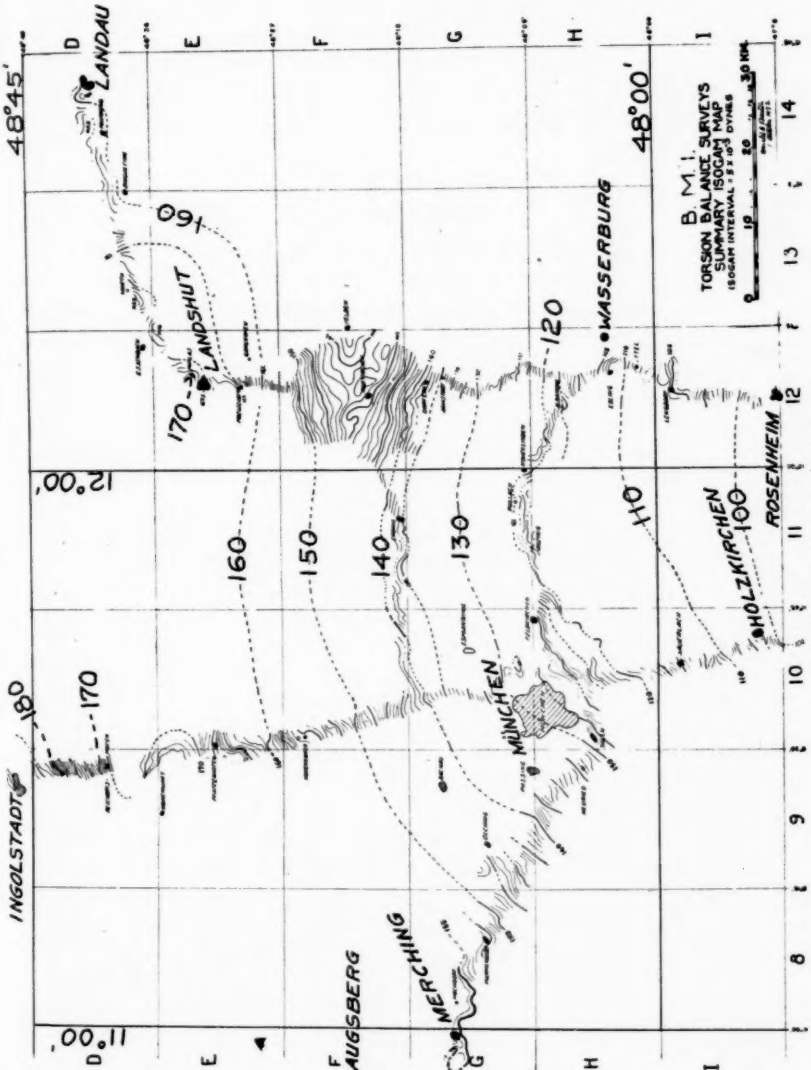


FIG. 5.—Observed variation of Δg_e.

The regional variation of gravity (Δg_s) is shown by the isogams of Figure 5. That regional variation shows the following significant characteristics: (1) a general, fairly uniform southward decrease in the intensity of gravity, (2) the suggestion of a broad, faint gravity nose through Landshut, and (3) slight curvature of the isogams as if around a basin, or else as if in conformity with another gravity nose through Augsberg.

INTERPRETATION

ISOSTATIC EFFECT

A southward decrease in Δg_s across the Munich basin would be produced by the root of the Alps if they are in isostatic equilibrium. According to the isostatic theory, the excess mass of the projection of the mountains above the general level must be compensated by an equivalent deficiency of mass in the root of the mountains. That subsurface deficiency of mass would produce a gravity minimum which would be concentric with the mountains and which will extend out from the edge of the mountains for a distance equivalent to two to three times the depth of the center of gravity of the deficiency of the root.

The isostatic effect of the Alps at a maximum could produce only a third of the observed variation of Δg_s; and no such isostatic effect need be postulated to explain the observed variation of Δg. The results of approximate calculations of the Δg_s which would be produced by an isostatically compensated Alpine mass are shown in Figure 6. The following assumptions were used: (1) The excess of mass of the Alps above the general level of the surrounding country is compensated by a corresponding deficiency in the mass of the root of the Alps; (2) the mean density of the Alps above ground is 2.5; (3) the Alps consist of a prism infinite in the east and west directions, 120 kilometers wide in north and south directions, rising 2.5 kilometers above the general level, and extending 25 or 50 kilometers below the general level; (4) the deficiency in mass is distributed uniformly through the vertical zone 0 to -25 kilometers; uniformly through the vertical zone 0 to -50 kilometers, uniformly through the vertical zone -25 to -50 kilometers, and uniformly through the vertical zone 0 to -100 kilometers. It is evident from Figure 6 that at a maximum, only a third of the observed variation of Δg_s north-south across the basin could be produced by an isostatic deficiency of mass in the root of the Alps. If any of the calculated Δg_s curves of the isostatic effect is subtracted from the curve of observed Δg_s, a resultant curve will be obtained which will indicate that at Rosenheim and Holzkirchen, the

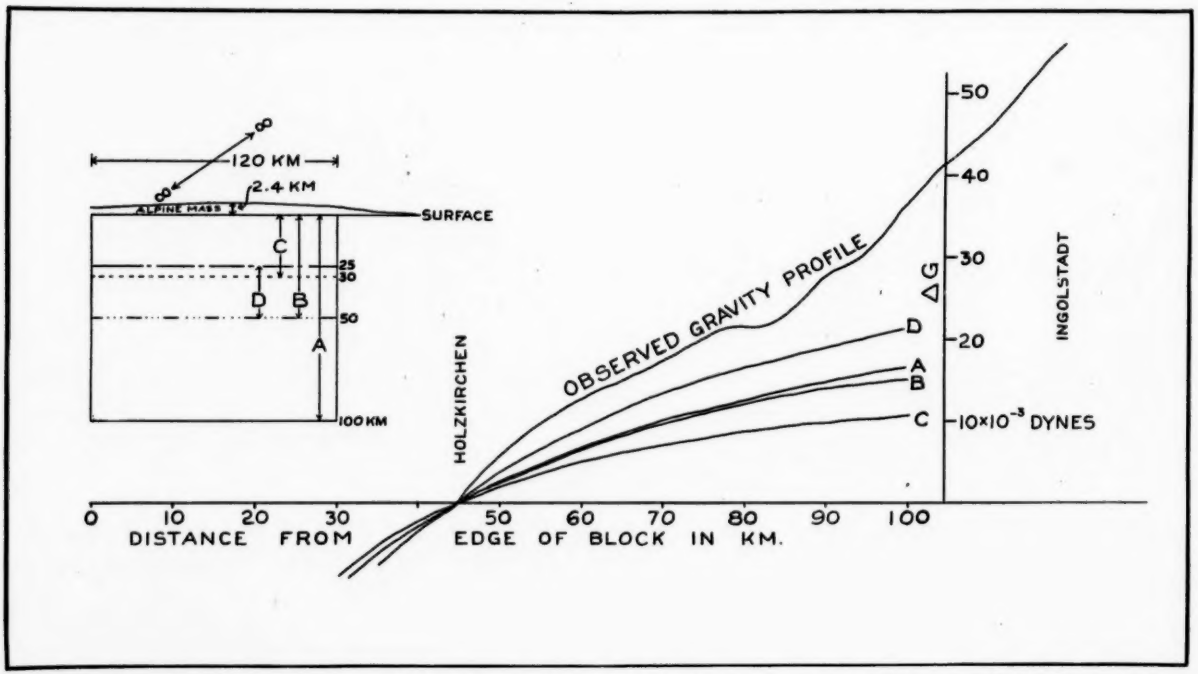


FIG. 6.—Observed variation of Δg, *versus* calculated gravitational effect of isostatically compensated Alpine mass. Distribution of deficiency of density in root of Alpine mass is assumed to be: A = uniformly 0 to −100 kilometers; B = uniformly 0 to −50 kilometers; C = uniformly 0 to −30 kilometers; D = uniformly −25 to −50 kilometers (relative density 0 to −25 kilometers = *nil*).

basement must be rising rapidly southward. Rosenheim and Holzkirchen lie well north of the front overthrusts; the front of the Bavarian Alps has been formed by overthrusting from the south; experiments seem to indicate that the front of the extensive yielding in overthrusting lies along a 45° shear line; the weight of the overriding overthrust sheets should tend to depress the basement, even for a considerable distance out into the foreland; the great thickness of the upturned Tertiary beds in the edge of the Alps would indicate correspondingly great thickness of the undisturbed Tertiary beds at Holzkirchen and Rosenheim. A southward dip of the basement at those places, therefore, is geologically more probable than a southward rise. The observed southward decrease of Δg_s is satisfactorily explained by the dip of the basement under the Tertiary beds.

DIP OF BASEMENTS

The divergent regional variation of Δg_s and of Δz_s seems to indicate divergent slopes between the surface of the crystalline basement and some higher surface of discontinuity between generally heavier rocks below and generally lighter rocks above.

The generally southerly decrease of gravity presumably is produced by a southward dipping upper surface of a thick series of rocks heavier than the overlying rocks. Geologically, such a dip is probable. The Mesozoic beds immediately north of the Danube in general dip gently southward. The Tertiary section must thicken greatly southward to produce the very great thickness of Tertiary beds which are upturned at the front of the Alps. The basement on which the Tertiary beds rest must dip southward. The unconsolidated Tertiary beds are composed predominantly of sands, clays, and gravel and, therefore, are relatively light. The underlying, presumably mostly lower Mesozoic beds are much more consolidated, comprise much limestone and sandstone, and presumably must be relatively light. The surface on which the Tertiary beds rest, therefore, presumably is a surface of density discontinuity with heavier rocks below. Quantitatively, with reasonable density assumptions, the observed gradient profile across the basin is produced by a geologically reasonable slope of that basement to the geologically reasonable thickness of unconsolidated sediments at Rosenheim and Holzkirchen of 13,000 feet ($\pm$ 25 per cent).

The southerly decrease of Δg_s across the basin mathematically also could be produced in whole or in part by a progressive horizontal variation in the character of the beds from unconsolidated sand and clay at the south to massive limestone at the north in a vertical sec-

tion 4,000 meters thick; geologically, such a gradation in the Munich basin is most improbable.

The west-southwesterly regional decrease of Z across the basin presumably must be produced by a west-southwesterly slope to the surface of the crystalline basement. Theoretically, that regional variation of Z_a could be produced also either by (1) a vertically uniform horizontal variation in magnetic permeability through a great vertical thickness, or (2) very special conformations of rock of high magnetic permeability, within the basement. Neither of those two possible causes of the observed southwesterly decrease in the intensity of ΔZ_a is probable geologically. Granitic-gneissic masses commonly have a higher magnetic permeability than most sediments. The surface on the crystalline rocks of the Bohemian massif dips under the Tertiary sediments. The most probable explanation of that observed regional variation of Z, therefore, is that the southwesterly slope of that surface presumably must continue across the basin under the Tertiary beds and under the Mesozoic beds.

The failure of the gravity picture to reflect the southwesterly dip of the surface of the crystalline basement across the basin and the failure of the magnetic picture to reflect the southerly dip of the contact between the Mesozoic beds and the Tertiary beds is the effect of the independence between the density and magnetic properties of rocks. The crystalline rocks of the basement must have a high density and a high magnetic permeability. The Mesozoic sediments, or at least the Jurassic-Triassic sediments, must have a relatively high density, probably about the same as that of the underlying crystalline rocks, and presumably a low magnetic permeability. The Tertiary sediments seem to have both a low density and a low permeability. The contact between the Tertiary and Mesozoic sediments therefore produces a gravity effect but no magnetic effect; and the contact between the sediments and the underlying crystalline basement produces a magnetic effect but no gravity effect.

The curvature of the magnetic isogams into a southwest trend in the southeastern part of the basin, in front of Salzburg, suggests the rise of the basement southeastward and the extension of the crystalline rocks of the Bohemian massif southwestward under the Austrian continuation of the basin, perhaps to connect with the crystalline core of the eastern Alps. The moderate depth of the granite at Wels in Austria shows that the crystallines extend out at least to the middle of the Austrian Tertiary belt.[4]

[4] That conclusion was reached before the writer came across Robert Schwinner's "Magnetismus in Bohmischer Masse und Ostalpen," *Gerlands Beitrage zur Geophysik*, Bd. 39, Heft 1 (1933), pp. 58–81.

The crystalline basement, somewhere on the western border of Bavaria or in Wuerttemberg, should begin to rise northwestward toward the granitic core of the Black Forest and Odenwald. The raying of the magnetic isogams in the southwestern part of the basin may indicate the beginning of the turn of the crystalline basement. Farther north, along the Danube, the corresponding bending of the isogams may have been lost in the large anomalies of the Alb and Donau magnetic axes.

VINDELICIAN RIDGE

The crest of the much disputed Vindelician ridge would seem not to cross the Munich Tertiary basin. The crystalline basement very likely would have been arched up to form a crystalline ridge as the core to the Vindelician ridge. The results of the magnetic survey of the basin indicate the absence of any such subsurface crystalline basement ridge, and the presence of a generally plane west-southwesterly dip of the basement across the basins. The results of the torsion-balance survey indicate the absence of any large structural ridge east-west across the basin, and indicate the presence of a fairly uniformly southerly dip of the basement under the Tertiary beds. The presence of a Vindelician ridge across the basin presumably should be suggested at least faintly, either by one or the other or by both of the methods (torsion balance and magnetometric). The absence of the slightest suggestion of the presence of any such ridge across the basin indicates that presumably no Vindelician ridge crosses the Munich Tertiary basin.

The position of the crystalline core of the Vindelician ridge south of the present Munich Tertiary basin would be consistent with the results of the B. M. I. surveys and would be suggested by the presumable continuation of the Bohemian crystalline massif southwestward under the upper Austrian belt of Tertiary formations.

WEST FLANK OF BOHEMIAN MASSIF

One of the problems of the B. M. I. geophysical surveys was to determine the character and steepness of the dip of the surface of the crystallines from the Bohemian massif west-southwestward under the Tertiary beds. In the area north of Regensburg, a north-south fault of considerable throw marks the contact between crystalline rocks of the Bohemian massif on the east and the Mesozoic sediments on the west, and west of the fault there is a large north-south syncline in which the only Cretaceous beds north of the mountains outcrop, overlying the Jurassic beds. From the vicinity of Regensburg south-southeastward to Hofkirchen, a fault is postulated also for the south-

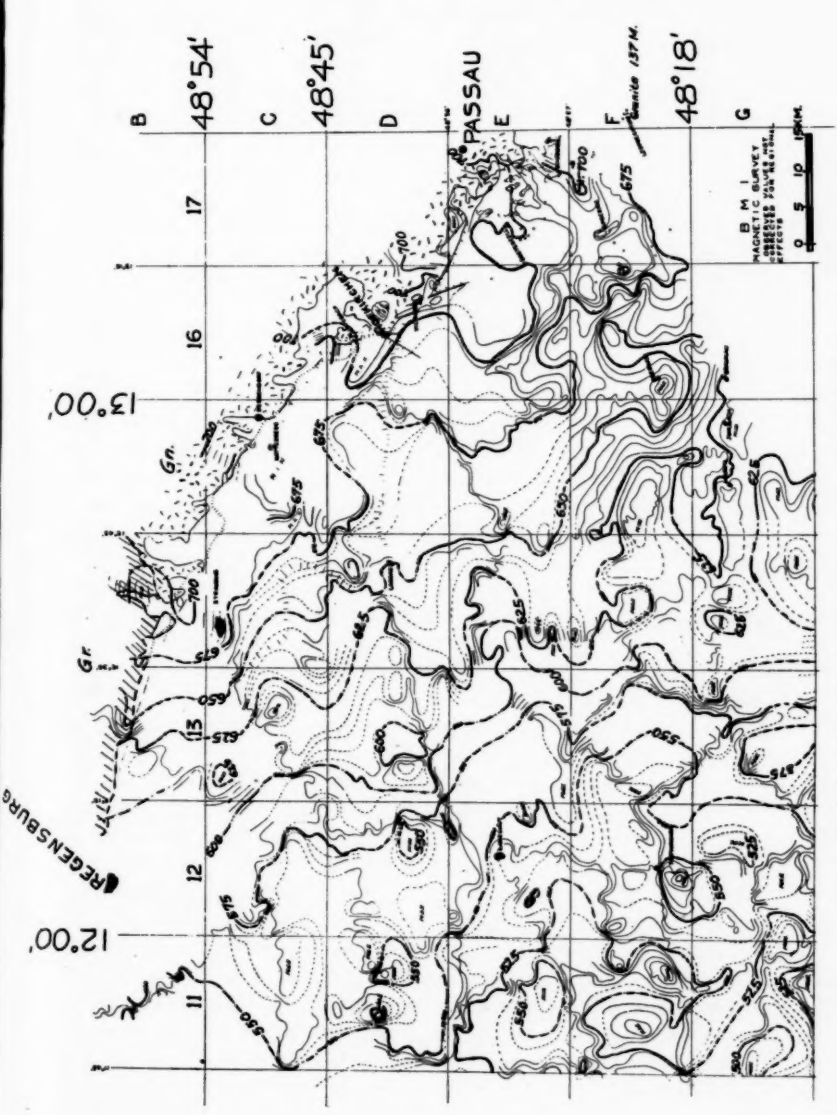


FIG. 7.—Variation of Δz, along front of Bohemian massif from Regensburg to Passau.

west front of the Bohemian massif. Over that stretch, the Danube flows at the foot of the edge of the crystalline rocks of the Bohemian massif. But from Hofkirchen past Passau, the Danube flows across the crystalline rocks, and a cross (northeast-southwest) fault is shown by Schuster's map at Hofkirchen. The structural block southeast of Hofkirchen geologically seems to have been uplifted; or the structural block northwest of Hofkirchen and in front of the crystallines geologically would seem to have been dropped down.

The broad flat-topped magnetic maximum in the area south of Hofkirchen, and west and southwest of Passau, and the magnetic minimum which extends from the vicinity of Hofkirchen northwestward along the Danube are in agreement with the picture of the relatively uplifted block south and west of Passau and Hofkirchen and the relatively down-dropped block northeast of Hofkirchen (Fig. 7).

The throw of the Danubian fault from Regensburg to Hofkirchen, on the basis of the magnetic data would seem not to be large. That fault brings the sediments in fault contact with the crystalline rocks. If the throw of the fault were large, there would be a sharp jump in the magnetic intensity at the contact. A sharp jump was observed on a traverse across the contact a short distance northwest of Deggendorf; but on the other traverses across the contact, its presence was dubiously reflected in the observed magnetic picture. There are two contrasting *a priori* alternatives in regard to that Danubian fault: (1) the sediments may have transgressed up the southwesterly dipping surface of the crystalline rocks, and a fault of moderate throw (100–200 meters) may have dropped the basinward sediments down only that moderate distance; or (2) progressive movement along the fault may have carried the basement of the basinward block down concomitantly with the general subsidence of the basin and with the deposition of a thick prism of sediments in the basin. Under the second hypothesis, there would be great thickening of the Tertiary sediments only a short distance out from the fault. The slight magnetic anomaly at the contact indicates that the throw of the Regensburg-Hofkirchen fault is 100 or 200 meters rather than 1,000 or 2,000 meters.

Three westward facing structural scarps, or extra steep slopes, presumably fault scarps, on the subsurface flank of the Bohemian crystalline massif are suggested by closer spacing of the isogams along certain zones. Faint regional features are obscured by the numerous lesser features. But if the isogams are smoothed out as well as possible to show their normal or regional course without regard to the lesser, local irregularities, there seems to be less than normal spacing between the 575- and 625-gamma isogams, in the zone from Strauburg south-

southeastward along the 650-gamma isogam, and along a parallel slightly farther northeast and partly along the 675-gamma isogam and partly along the 700-gamma isogam. This latter zone of steeper than normal magnetic gradient suggests the presence of a structural (subsurface) fault scarp forming the west-southwestern edge of the uplifted basement block in front of Hofkirchen and Passau. The zone between the 575- and 625-gamma isogams is closely on the prolongation of the fault which extends northward from Regensburg. The closer than normal spacing of the isogams of that zone suggests that the Regensburg fault extends far southward under the cover of the Tertiary sediments; unfortunately the survey did not cover the area immediately south of Regensburg; and that zone of closer than normal spacing of the isogams cannot be followed in the data of the survey directly up to the south end of the surface exposure of the fault.

THICKNESS OF TERTIARY SEDIMENTS

The thickness of the prism of unconsolidated sediments from Ingolstadt southward across the basin to Holzkirchen can be calculated approximately from the results of the torsion-balance survey if the following approximately justifiable assumptions are made: (1) that increase in density between the unconsolidated and consolidated series is concentrated at the contact between the two series; (2) that the base of the unconsolidated series crops out at Ingolstadt; and (3) that the effect from isostatic compensation of the Alps is negligible. The calculation can be made graphically, or by ordinary formulae used in torsion-balance work. Our qualitatively quantitative calculations from the torsion-balance data indicate that the thickness of the unconsolidated sediments is as follows.

	Feet	*Per Cent*
At Munich	8,000	±25
Holzkirchen	13,000	±25
Landshut	1,500	±25
Taufkirchen		
Normally	6,000	±25
Top of prospective structure	5,200	±25
Rosenheim	13,000	±25

The errors probably are all of the same algebraic sign and approximately of the same relative magnitude.

Geologically, the unconsolidated sediments presumably are the Tertiary formations, and the Mesozoic are the consolidated sediments; but the consolidation, and consequently the density of the Cretaceous, may be closer to that of the Tertiary than to that of the Triassic and Jurassic; the Cretaceous should then be included with the unconsolidated sediments.

MAJOR STRUCTURES

HERCYNIAN RIDGES

A broad Hercynian (northwest-southeast) ridge through Landshut is suggested by the results of the torsion-balance survey, which partially corroborate the northwest-southeast positive anomaly on Schütte's map of the Bouguer anomalies from the pendulum determinations of gravity in southern Germany. The B. M. I. torsion-balance survey mapped the presence of a broad, somewhat complex northwest-southeast maximum through Landshut which would correspond with the Landshut part of that maximum on Schütte's map.[5] The B. M. I. torsion-balance and magnetic surveys indicate that the anomaly at Ingolstadt is produced by sharp local structure and suggest that the Ingolstadt and Landshut anomalies should not be connected, until further evidence indicates an actual connection. From the few data, the writer would infer that the Landshut ridge does extend northwestward but that it probably crosses the Danube somewhere east of Ingolstadt.

The results of the magnetic survey do not suggest the presence of the Landshut ridge.

The results of the two types of surveys seem to indicate: (1) that deformation of the crystalline basement is not sufficient to produce an appreciable effect in view of the great depth of the basement, and (2) that the Mesozoic formations and perhaps the surface of the Mesozoic basement under the Tertiary formations must be deformed sufficiently to affect the variation of gravity at the surface. The torsion-balance data of the single traverse are rather scanty for much interpretation of the ridge.

The results of the torsion-balance survey suggest that there may be a parallel and similar ridge through Augsburg.

REGENSBURG SYNCLINE

The southward prolongation of the Regensburg syncline under the Tertiary formations is suggested by the results of the single torsion-balance line eastward from Landshut to Landau. A trough of minimum is shown by Schütte's map of the Bouguer anomalies as lying in front of the Bohemian massif. North of Regensburg, the minimum tends to coincide approximately with the faulted Regensburg syncline. The results of the torsion-balance survey tend to corroborate the presence of that trough of minimum in the Landau area.

The results of the B. M. I. magnetic survey do not reflect the presence of the syncline.

[5] K. Schütte, *Karte der Schwereabweichungen Süddeutschland* (Munich, 1930).

North of Regensburg, the broad faulted syncline seems to have been formed by the down-warping of Mesozoic formations in reference to the area west and by down-faulting of those formations in reference to the Bohemian crystalline massif. The syncline, therefore, may not affect the surface of the crystalline basement to the same extent that it affects the Mesozoic formations or may not affect it at all. The results of the B. M. I. magnetic survey would seem to indicate that within the area of the Munich Tertiary basin, the Regensburg syncline does not appreciably affect the crystalline basement.

The question is open whether within the Munich Tertiary basin: (1) the Landshut ridge is the effect of positive arching along a Landshut structural axis; or (2) the effect of the negative down-warping of the Regensburg syncline. The isogams of the torsion-balance survey agree qualitatively with Schütte's isogams of the Bouguer anomalies. In the extreme eastern part of the basin, the isogams tend to bend into parallelism with the front of the Bohemian massif. In that area, the west-southwestward dip of the surface of the crystalline complex under the sedimentary formations may be producing an appreciable effect on the variation of gravity at the surface. It is possible also that the Mesozoic basement under the Tertiary formation may rise east-northeastward up toward the Bohemian massif. North of Regensburg, the syncline seems to have been produced by negative movement in front of the Regensburg fault. Similar structural movement south of Regensburg, within the Tertiary basin, would produce a Landshut ridge and a continuation of the Regensburg syncline, which in turn would produce the observed variation of gravity. The Landshut ridge, however, would not represent the effect of a positive axis of deformation.

BASALTIC STRUCTURES ALONG DANUBE

A line of previously unsurmised structures with basaltic cores was mapped along Danube River from Vohburg to Ulm. The Ingolstadt structure is one of the most pronounced of those structures and is the only one which is crossed by both the magnetic and the torsion-balance surveys. It has a sharp gravity maximum and a sharper magnetic maximum. The magnetic isogams are shown in Figure 8. The north-south profiles of relative gravity (Δg_s), of the horizontal gradient of gravity (U_{xz}), and of relative Z_s are shown in Figure 9. The amplitude of most of the residual anomalies within the area of the survey is ± 25 gammas from the regional value of Z_s of Figure 4, although a few residual anomalies have an amplitude of $+50$ or -50 gammas. The residual maximum of the Ingolstadt structure has an

amplitude of 250 gammas. Part, approximately half, of the steep north gradient and steep southerly decrease of Δg is regional and has no relation to the Ingolstadt structure. The gravity maximum is not as sharp or as flat topped as the magnetic maximum. Their respective shapes indicate that the extra dense mass is not co-extensive with the magnetically extra-permeable mass, but is somewhat larger and ex-

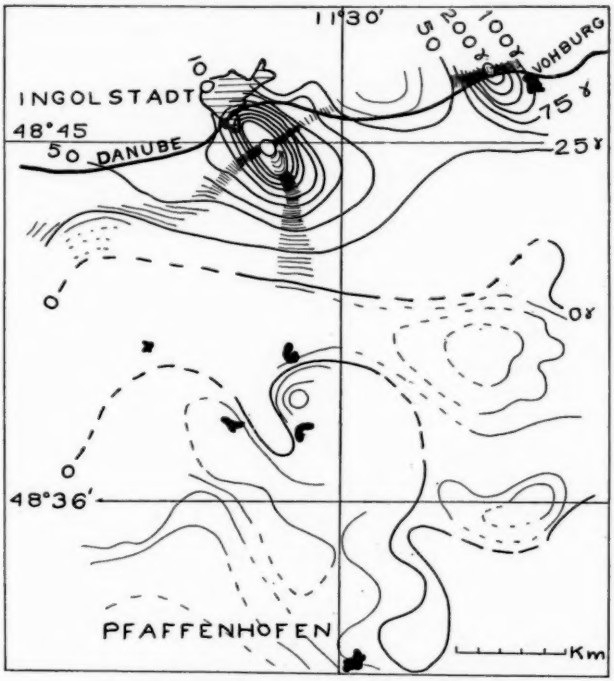


FIG. 8.—Observed variation of Δz, Ingolstadt area.

tends somewhat deeper. The form of the magnetic anomaly indicates that the extra-permeable mass has a crudely disc-like form. Crude calculations in which the magnetic profile was treated as if it were a gravity profile indicate a depth to its top of approximately 3,000 feet and a thickness of approximately 800 feet for the disc. The high magnetic permeability of the rock of the disc suggests a basaltic character.

The Vohburg (C-10, Fig. 8), Weichering (D-9), and Strass (D-8) magnetic maxima are similar anomalies and presumably likewise represent basaltic, probably laccolithic, intrusions (Figs. 3 and 10).

This Danube line of anomalies is continued toward the west by the Oberndorf (D-7), Bergau (E-F-5), and southeast of Ulm (F-4) maxima (Figs. 3 and 10). They are areally large and have respective amplitudes of +35, +35, and +20 gammas. They are no larger in area or amplitude than the larger maxima out in the Tertiary basin and may be produced by the same type of irregularity in magnetic permeability, whatever it may be. But on account of their association

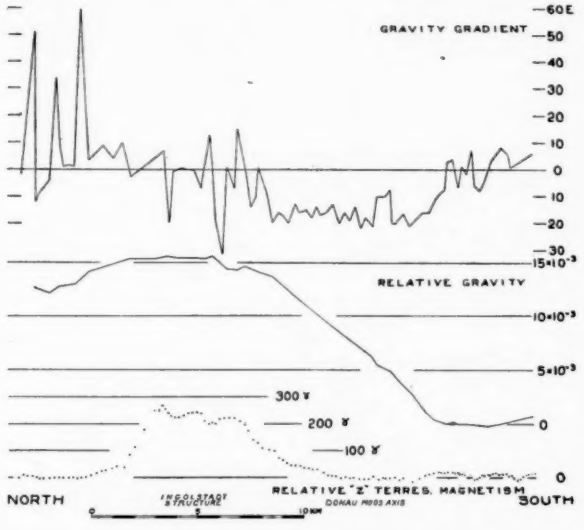


FIG. 9.—Profiles gravity gradient (U_{zz}), relative gravity (Ug_z), and relative magnetic vertical component (Δz_a), across Ingolstadt anomaly and Donau Moos axis.

with the Vohburg, Ingolstadt, Weichering, and Strass maxima, they may be the effect of deeper basaltic intrusions.

This Danube line of structures with basaltic cores lies along the postulated Danube fault, which seems to have guided the course of Danube River between Ulm and Vohburg and which separates the Tertiary from the Jurassic formations. The fault must be deep in origin and presumably must extend far down into the basement. Basalt or other igneous rock of high magnetic permeability seemingly must have come upward along the fault plane to form the laccolithic intrusions of Vohburg, Ingolstadt, Weichering, and Strass in the Jurassic or Triassic sediments.

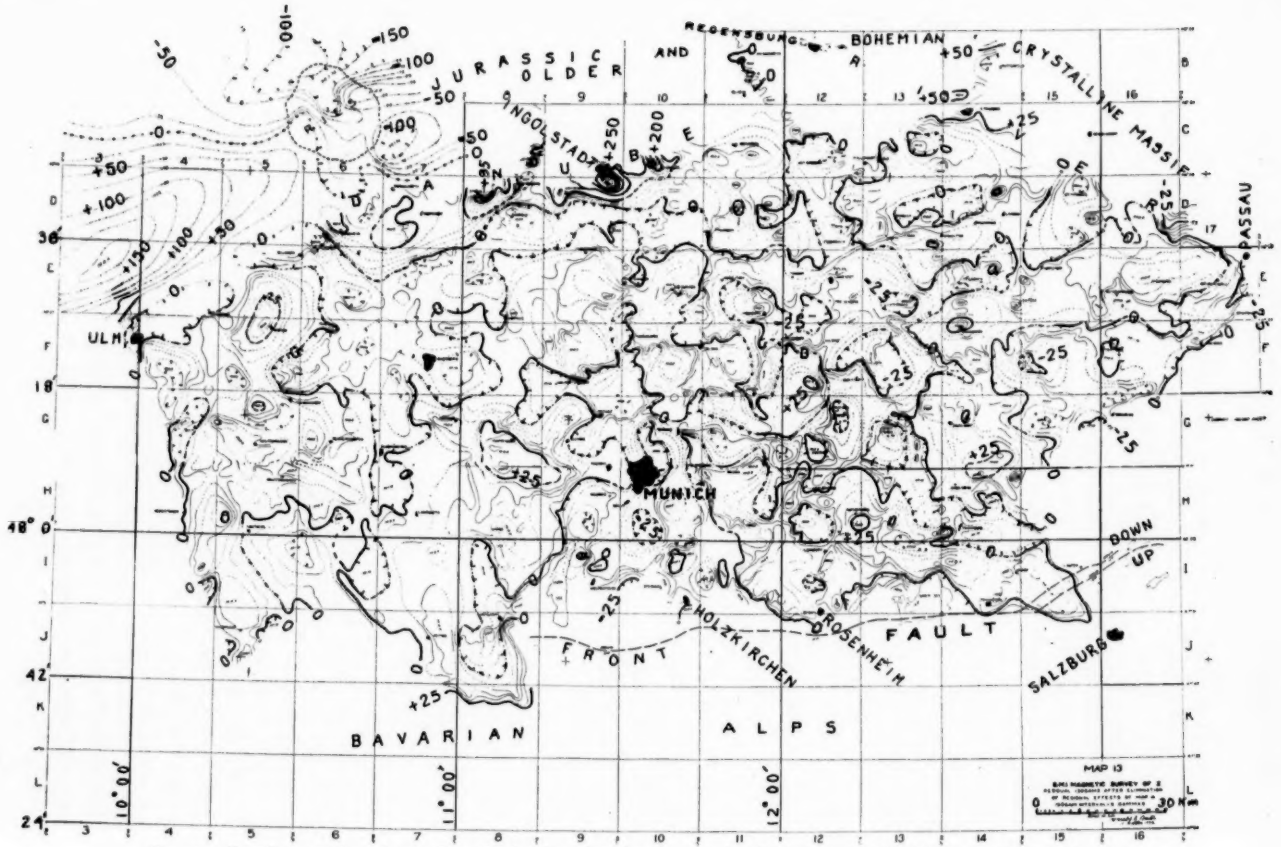


FIG. 10.—Local anomalies of Δz, after elimination of regional anomaly of Figure 4. Residual isogams after elimination of southwest regional decrease. Isogam interval, 5 gammas. Dotted isogams based on Haussmann's data.

FIG. 10.—Local anomalies of Δz, after elimination of regional anomaly of Figure 4. Residual isogams after elimination of southwest regional decrease. Isogam interval, 5 gammas. Dotted isogams based on Haussmann's data.

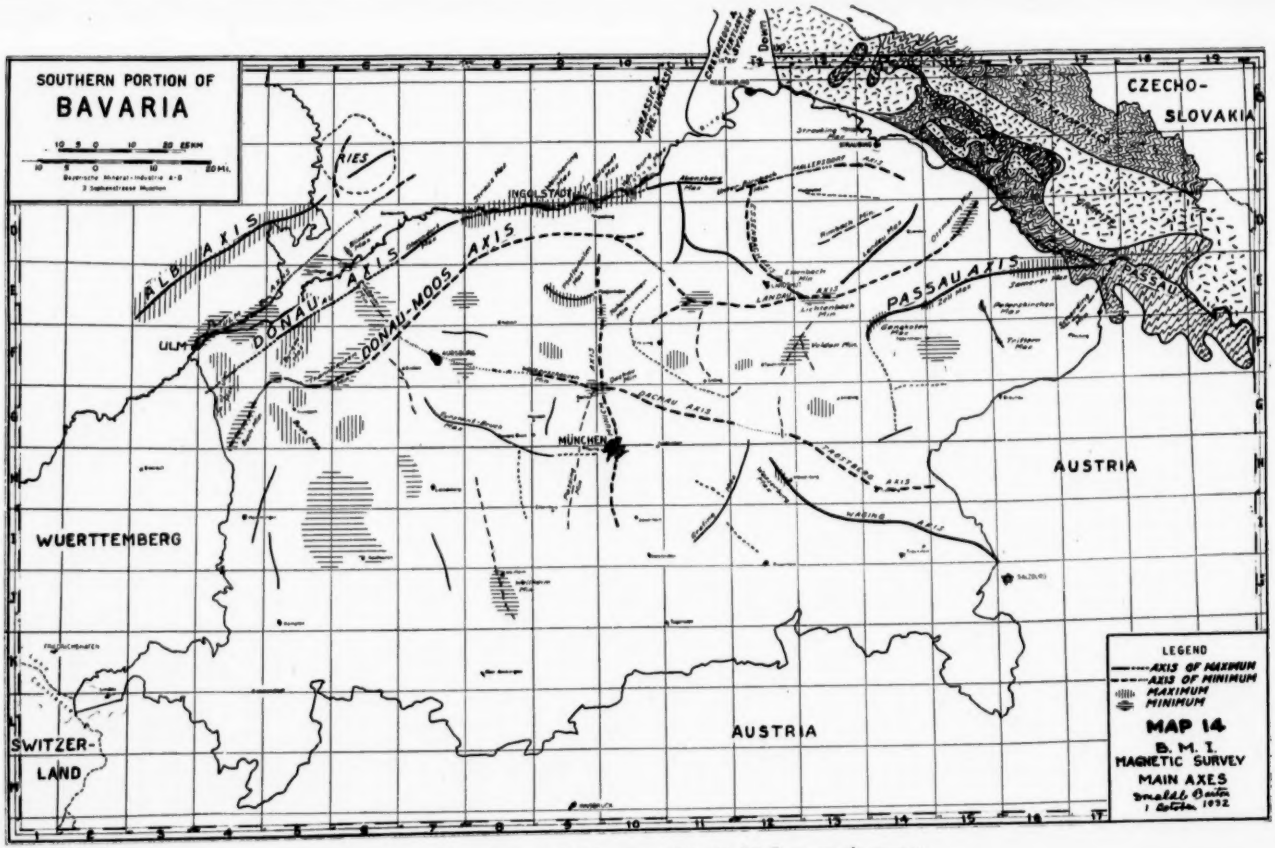


FIG. 11.—Axes indicated and suggested by B. M. I. magnetic survey.

ALB BASALTIC AXIS

The Alb magnetic maximum (Fig. 10) on the northwest edge of the area surveyed indicates the presence of an elongate intrusion or a line of intrusions parallel with the Danube line. The data mostly have been taken from Haussmann.[6] The results of the B.M.I. line from Ulm northwestward corroborate its presence although they place the southeast slope of the ridge of maximum north of Ulm rather than east of Ulm, as Haussmann delineates it. The writer agrees with Haussmann that the Alb axis of magnetic maximum must reflect the presence of a large basic igneous intrusion at depths of 3–8 kilometers. But Haussmann's magnetic stations are too widely scattered to show whether there is one large intrusion or whether there are a series of intrusions whose magnetic effects merge and give the effect of one large intrusion.

DONAU MOOS AXIS

The Donau Moos axis of magnetic minimum (Fig. 10) south of the Danube axis of maximum is not so sharp or definitely delineated. Yet it does seem to exist and to parallel that Danube axis. There is a suggestion that the line is made up of a series of local minima, which are paired with, and southeast of, the maxima of the Danube line. A volcanic plug which has a large vertical dimension may act as a bar magnet; if it is vertical or nearly vertical and has only induced magnetism, its upper pole will produce a maximum and its lower pole a much weaker minimum. If a volcanic plug dipped 75°–80° toward the southeast in Bavaria, and if it were polarized, the lower pole would tend to produce a weak minimum to the southeast of the maximum. This minimum does not indicate the presence of any structure separate from the volcanic plug and must not be confused with the ordinary minima which represent lows in the ordinary (positive) intensity. South of Ingolstadt, there is a gravity minimum which is fully as definite as the magnetic minimum. The two minima are offset from each other 5 or 6 kilometers, but they appear to belong together and are reflecting a common structural feature. But if the two are produced by a common structural feature, the minimum can not be produced by the lower pole of an Ingolstadt volcanic plug, but must be produced by some structural feature which is independent from, but perhaps associated with, the Ingolstadt structure. The gravity minimum, presumably, must indicate a syncline. It therefore would tend to indicate that the Donau Moos axis indicates a syncline (or graben).

[6] Karl Haussmann, "Magnetische Messungen um Ries und Dessen Umgeburg," *Abh. d. k. Preuss* (Akademie der Wissenschaff, 1904).

LESSER MAGNETIC ANOMALIES

The heterogeneous jumble of more or less irregular residual magnetic maxima and minima within the Tertiary basin (Fig. 8) at first sight gives little suggestion of any fundamental underlying structural plan in connection with the anomalies. It is probable that a considerable part of the anomalies are not produced by geologic structure.

Practically all detail magnetic surveys have many anomalies which seemingly are not produced by geologic structure. The data usually are not sufficient to determine what is the cause of these anomalies. Some of them presumably are apparent rather than real and are produced by observational errors, by accidental coincidence of several surficial anomalies of the same sign in consecutive stations, and by the incomplete covering of the area by the survey and the consequently inaccurate inference in regard to the course of isogams in the unmapped areas between surveys. Others of these anomalies presumably are produced by variations in the content of magnetite and ilmenite in the sediments. Many of the anomalies of Figure 1 presumably are of one of these types or a combination of these types.

A certain more or less definite pattern does stand out, however, after closer study of Figure 10 and suggests some fundamental underlying structural plan and cause for many of the anomalies. The magnetic axes are shown on Figure 11. Some of them, such as the Alb and Danube axes, plainly are actual axes and must reflect geologic structure in the subsurface. Others of the lines may be the result of subjective connection of accidentally aligned independent local anomalies.

The Passau axis, however, can be seen probably to be the effect of differences of magnetic permeability in the basement. The Passau axis of maximum is well delineated. Its amplitude is above the average of the anomalies other than those of the Alb and Donau axes. It has been crossed by sufficient traverses to indicate that it does exist. But unfortunately it does not cross or approach any of the torsion-balance work. The eastern end of the maximum, as the B. M. I. mapped it, extends into the area of the outcrop of the granite and the metamorphic rocks; and for a considerable distance in the area slightly farther west, the depth to the granite and the metamorphic rocks can not be great. A nose of metamorphic rocks projects from Passau eastward into the area of granite exactly on the prolongation of the Passau axis of maximum. From the B. M. I. magnetic data and the other data which are available, genetic connection between that nose of metamorphic rocks in the granite can not be proved. But it seems

probable that the Passau axis of maximum is being produced by some such geologic feature within the crystalline basement. The center of gravity of the feature can be as deep as 5,000 meters, but can be shallower.

ABSENCE OF FOLDING PARALLEL WITH ALPINE FRONT

The determination of the presence or absence of folding parallel with, and in front of, the Alps was an important problem for these surveys. Northward thrust from the Alps against competent beds within the beds of the Tertiary basin should be expected to produce folds in front of, and parallel with, the front of the Alps. But thrust against a prism of wholly incompetent sediments should produce yielding along overthrusts but no folding ahead of the overthrusts.

The presence of folding in front of, and parallel with, the edge of the Alps is not indicated or suggested by the results of the torsion-balance and magnetic surveys, although there is suggestion of faulting. The failure of both the magnetic and torsion-balance surveys to indicate or suggest the presence of such folding is not conclusive proof of its absence. It is conceivable that there is no vertical variation of magnetic permeability. Such folding, therefore, would produce no magnetic anomalies. The absence of any vertical variation of density is possible, but increase of compaction, and therefore of density, with depth is probable. The increase of density with depth, however, might be so slight that the folding would produce very faint anomalies. The close spacing of the torsion-balance stations was used so that faint anomalies might possibly be detected. The writer was unable to recognize any anomalies which he would interpret as indicating such folding. The absence of indication or suggestion of the folding by the results of the geophysical surveys is evidence, therefore, although not finally conclusive evidence, that folds of moderate or large size and amplitude are not present in front of the Alpine overthrusts.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 97-105. 4 FIGS.

MAGNETIC VECTOR STUDY OF KENTUCKY AND SOUTHERN MICHIGAN[1]

W. P. JENNY[2]
Houston, Texas

ABSTRACT

The principle of the magnetic vector method is briefly explained.

The salient geological features of Kentucky are investigated as to their regional magnetic effects. It is found that the Western and Eastern geosynclines show up magnetically as negative anomalies, but that also the Cumberland River arch and the Lexington dome show up as negative anomalies. From this follows that some of the outcropping beds in Kentucky are of a higher magnetic permeability than the underlying beds and Basement complex.

The study of the magnetic vector map in Michigan reveals a number of magnetic high trends, which are shown to correspond to known structural trends, such as the Howell-Owosso anticline and the Muskegon anticline. The deepest area of the Michigan basin is indicated by a negative magnetic anomaly.

Practical value and application of the magnetic vector maps to field problems is explained by the example of the newly discovered Hart field. Apart from the valuable information obtained by magnetic investigations alone, such investigations are of great help in the interpretation of data gained by other geophysical methods.

INTRODUCTION

The principle of the magnetic-vector method, which has been fully explained elsewhere,[3] may be briefly summarized as follows.

In order to obtain the direction in space and the intensity of the magnetic lines of force as due to local structures, the "normal" values of the earth's magnetic field have been deducted from the absolute measurements at the United States Coast and Geodetic Survey's stations of the declination, and of the vertical and horizontal magnetic intensities.

The differences between the absolute and "normal" vertical and horizontal intensities have been combined into a vector triangle, indicating the direction and intensity of the local magnetic force. The vector triangles have been plotted on the maps at their respective stations, by turning the triangles through 90° around the horizontal component (which is the dashed line starting at the station point)

[1] Manuscript received, October 26, 1933.

[2] Geologist and geophysicist, 2102 Bissonnet Avenue.

[3] W. P. Jenny, "Magnetic Vector Study of Regional and Local Geologic Structure in Principal Oil States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol., 16, No. 12 (December, 1932). "Structural Trends in Florida," *The Oil Weekly* (October 2, 1933).

into the plane of the map. A black station point means that the magnetic force is directed toward the station; a hollow station point means that the magnetic force is directed away from the station, as indicated by the arrows in the legend.

KENTUCKY

The salient geological features of Kentucky are the Cumberland River arch, the Western geosyncline, the Cincinnati arch, the Lexington dome, the Eastern geosyncline and the Pine Mountain thrust fault, as set forth on the inset of Figure 1. The most westerly corner of Kentucky is covered by Quaternary, Tertiary, and some Cretaceous. East of the Cumberland River arch only rocks of Pennsylvanian age and older are found, which are subdivided by the legend of the geologic map of Kentucky[4] as follows:

Pennsylvanian	Conemaugh
	Allegheny
	Pottsville
Mississippian	Chester
	Meramec
	Osage
Devonian	
Silurian	
Ordovician	Cincinnatian
	Champlainian

The Meramec crops out along a belt east and south of the Western geosyncline and is the outcropping formation along the axis of the Cumberland River arch west of the syncline.

The core of the syncline consists of Conemaugh.

The Lexington dome has its apex in the general neighborhood of Lexington, where the beds of the Champlainian crop out, surrounded by a vast area of Cincinnatian.

The whole Eastern geosyncline and surroundings are covered by the Pottsville to within a distance of about 30 miles east of the axis of the Cincinnati arch.

It is most characteristic that the Cumberland River arch and the Lexington dome show up as negative magnetic anomalies. From this we must conclude that the Chester or some beds of the Pennsylvanian are of a greater magnetic permeability than the Meramec and further that the Cincinnatian, Silurian, Devonian, and Osage are of a greater magnetic permeability than the Champlainian and lower formations.

The areas of the two geosynclines are characterized by magnetic negative anomalies.

[4] W. R. Jillson, "Geologic Map of Kentucky," *Kentucky Geol. Survey* (1929).

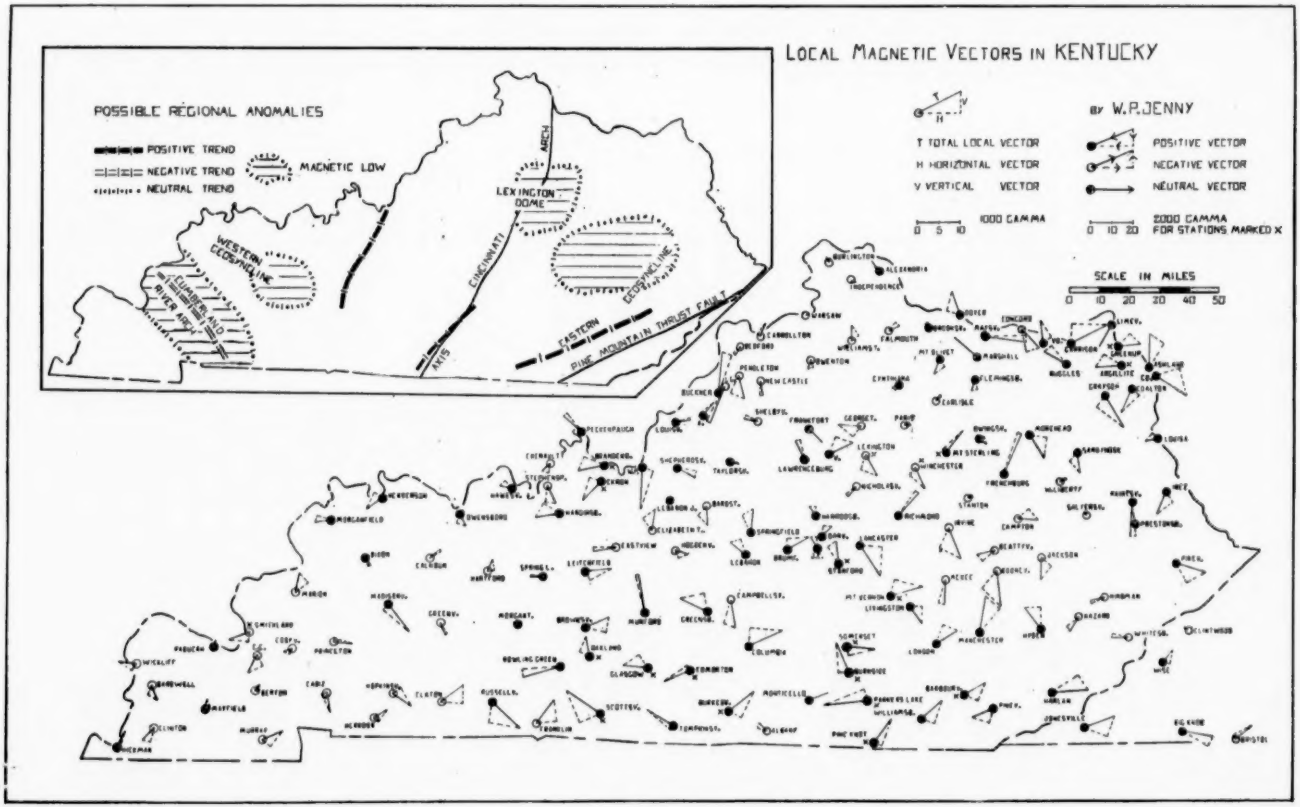

LOCAL MAGNETIC VECTORS IN KENTUCKY
BY W.P.JENNY
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
1000 GAMMA
2000 GAMMA FOR STATIONS MARKED X
SCALE IN MILES
POSSIBLE REGIONAL ANOMALIES
POSITIVE TREND
NEGATIVE TREND
NEUTRAL TREND
MAGNETIC LOW
ARCH
LEXINGTON DOME
CINCINNATI AXIS
EASTERN COALFIELD
EASTERN COALFIELD
CUMBERLAND RIVER ANTICLINE
WESTERN COALFIELD
PINE MOUNTAIN THRUST FAULT

FIG. 1

The southern part of the axis of the Cincinnati arch seems to be indicated by a positive magnetic trend.

Another regional positive trend about parallel with the Cincinnati arch may be perceived in the northern central part of Kentucky, starting between West Point and Brandenburg and extending southward to beween Morgantown and Brownsville.

A third regional positive trend, about parallel with the Pine Mountain thrust fault, possibly extends from Pine Knot to Hyden.

The interpretation of the magnetic vectors in Kentucky encounters increased difficulties, because the magnetic susceptibility of some of the outcropping beds appears to be so great that large magnetic "highs" and "lows" may be expected as a result of stratigraphic changes only, without any structural significance. Without adequate support from geologic data, it is therefore not possible to say whether regional trends are mainly due to structural or stratigraphic features and the same holds true for the large number of local anomalies indicated by the vectors.

The shallowness of the magnetically active horizons should, however, prove to be of advantage for the interpretation of local anomalies, if they are sufficiently detailed by magnetometer surveys.

SOUTHERN MICHIGAN

Southern Michigan is a large structural basin, the deepest area of which lies between Mount Pleasant, Saginaw, and Lansing. The beds dip from all sides at a rate of 25–50 feet per mile toward this central area.[5]

A sheet of unconsolidated glacial drift with an average thickness of 200 feet covers the whole of Michigan. Below this sheet the Pennsylvanian crops out in the central part of the basin and the Mississippian, Devonian, and Silurian surround this core in belts of varying widths.

Among the few minor structures known in Michigan[6] are: the Saginaw anticline east and north of Saginaw; the Howell-Owosso anticline, extending northwest from Ann Arbor toward Howell, Owosso, and St. Johns; the Muskegon anticline north and east of Muskegon; and the Mount Pleasant anticline east of Mount Pleasant.

Different theories have been advanced to explain the origin of these folds. They may be connected with the Cincinnati and LaSalle

[5] G. W. Pirtle, "Michigan Structural Basin and Its Relationship to Surrounding Areas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 2 (February, 1932), pp. 145–52.

[6] R. B. Newcombe, "Oil and Gas Development in Michigan," *Michigan Geol. Survey Pub. 37*, Pt. 3, Geol. Series 31 (1928). "Geology of Muskegon Oil Field, Muskegon, Michigan," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 2 (February, 1932), pp. 153–68.

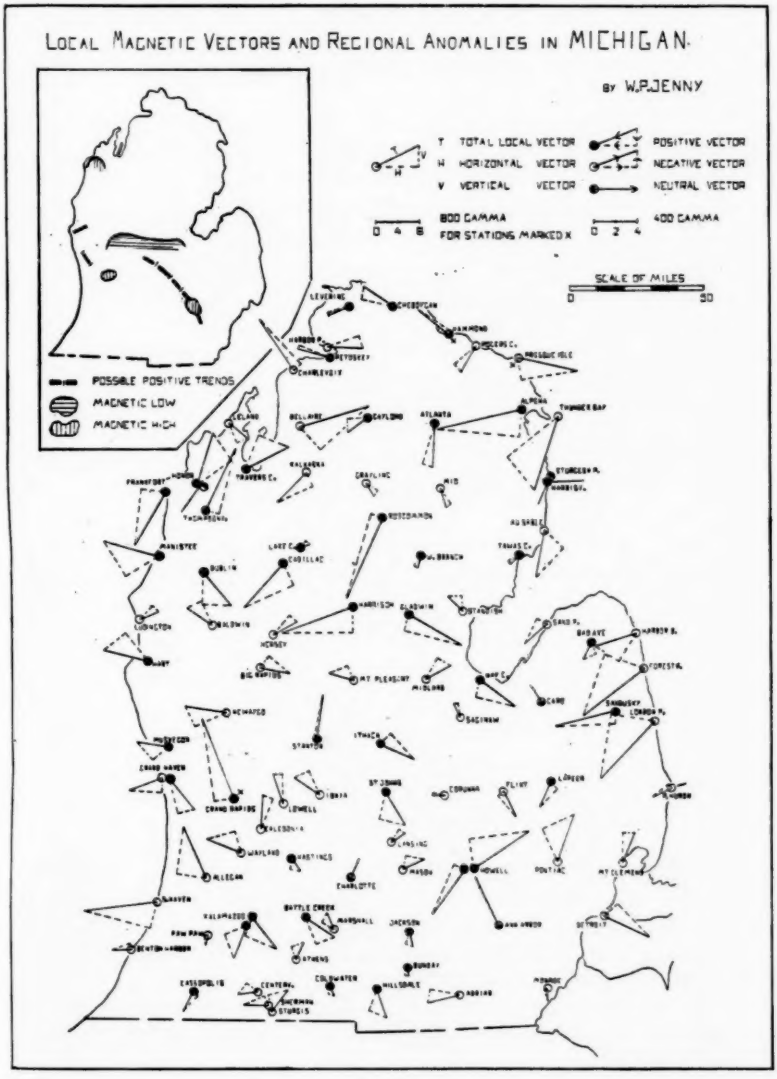

LOCAL MAGNETIC VECTORS AND REGIONAL ANOMALIES IN MICHIGAN.
BY W.P.JENNY
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
800 GAMMA
FOR STATIONS MARKED X
400 GAMMA
SCALE OF MILES
POSSIBLE POSITIVE TRENDS
MAGNETIC LOW
MAGNETIC HIGH

FIG. 2

anticlines, or they may be due to more local stresses and lateral pressures, as a consequence of the settling of the basin. Probably both factors should be considered and some unconformity between deeper and shallower structure may reasonably be expected, mainly as the result of salt flowage in the Salina.

Since the glacial drift and the shallow formations do not seem appreciably to influence the magnetic field, it appears that the magnetic anomalies may be mainly attributed either to the structures or to the

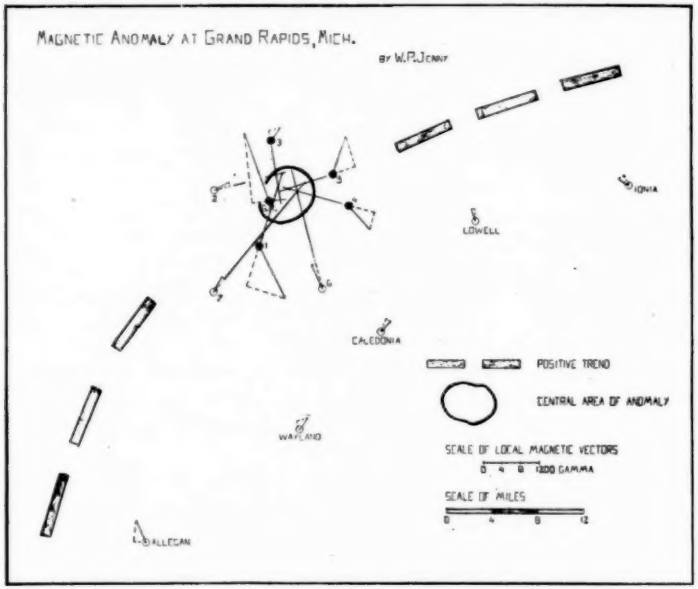


FIG. 3

mineral content of the pre-Cambrian. From a comparison of the vector map (Fig. 2) with known structures, we conclude that the majority of magnetic anomalies may safely be interpreted in terms of structures: positive vectors indicating anticlinal structures, negative vectors indicating synclinal structures.

The negative magnetic vectors at Midland, Mount Pleasant, Big Rapids, and Newaygo are indicative of the large depression in the heart of the basin.

The horizontal vector at Ann Arbor points toward a "high" near Howell as indicated by the two vectors. The negative vectors at Flint,

Corunna, Lansing, and Mason all indicate a "high" trend extending from Howell toward St. Johns and possibly as far as Ithaca and Stanton. This magnetic trend should correspond with the known Howell-Owosso anticline and suggests a northwestward extension toward Stanton.

The positive vector east of Muskegon plainly suggests the known northwesterly anticlinal ridge, which at its intersection with a west-easterly ridge, formed the Muskegon anticline.

A large uplift is indicated by an anomaly of more than 1,500 gammas in the general neighborhood of Grand Rapids. The United States Coast and Geodetic Survey has made observations of the magnetic elements at 7 auxiliary stations near Grand Rapids. The local vectors at these auxiliary stations are represented in Figure 3 together with a few near-by vectors. The negative vectors at Allegan, Wayland, Caledonia, Lowell, and Ionia seem to indicate a regional magnetic "high" trend west, northwest, and north of these stations as indicated in the figure. Along this regional trend occurs the large positive anomaly of Grand Rapids. The vectors at Grand Rapids and at the 7 auxiliary stations all point toward a positive area with its center slightly east of Grand Rapids. It seems safe to interpret this anomaly as a large domal uplift along a regional anticlinal trend.

Another uplift is suggested by the vectors at Frankfort, Honor, and Thompsonville.

APPLICATION OF MAGNETIC VECTOR MAPS

In areas like Kentucky, where some of the outcropping beds appear to be of a higher magnetic permeability than the deeper strata, most of the vectors are necessarily connected with shallow and local anomalies. Some of these anomalies may correspond with actual structures, others with stratigraphic changes along the surface. Though only scant information as to regional and local structures may be gained by a study of this vector map, it will, however, be of great value for an intelligent planning of detailed investigations by the magnetometer.

For all these areas, like Michigan, where the deeper strata and the basement are of a higher magnetic permeability than the uppermost few thousand feet of sediments, the large majority of magnetic anomalies may be connected with structural features; some of the anomalies may, however, be caused by a variation of the magnetic permeability, brought about by changes in the mineral content of the magnetically active horizons. Due to the long distances between stations the magnetic vector maps at first sight mainly reveal only re-

gional structural features. For those stations, which are sufficiently close to local structures, the magnetic information gained from the vector map may, however, be connected with the local structures. In this respect we have already mentioned the vectors at Refugio, Conroe, Livingston, Mineola (Texas), Bastrop, Evangeline (Louisiana), Jackson (Mississippi), Oklahoma City, Eldorado (Kansas), and others.[7]

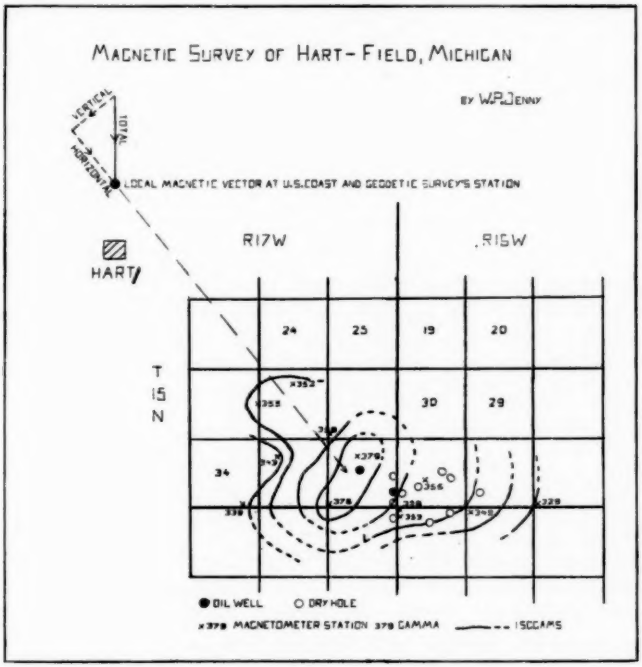


FIG. 4

The magnetic vector at Hart, Michigan, is another example where there exists a direct connection with a local commercial structure. The positive vector suggests a magnetic "high," southeast of Hart, which might correspond with an uplift with a possible northeast-southwesterly axis. Prompted by this suggestion, the writer has made a casual magnetic survey of the recently discovered Hart field in order to check the conclusions drawn from the vector map. Figure 4 shows

[7] W. P. Jenny, *op. cit.*

the locations of the first wells and the isogams based on 12 magnetometer stations. The isogams check fairly well with the contour lines drawn on the red beds of the Coldwater, but in contradiction to current geological conceptions, seem to be in favor of the local magnetic vector, suggesting a northeast-southwesterly trend of the structure. Though the production from the Traverse has been disappointing so far, there seems to be no doubt that the magnetic data indicate a considerable uplift.

It is, however, rather surprising that the magnetic "high" should so closely correspond with the structural "high" in the Traverse. The rule for Michigan will most probably be that the magnetic "high," which is caused by an anticlinal structure in the Basement complex, is considerably offset from the structural "high" in the Dundee or Traverse, mainly because of the several hundred feet of plastic salt and anhydrite beds, which lie between the upper and lower structure.

Since the gravimetric field may reasonably be assumed to show some influence of upper structures, it seems that a combination of gravimetric and magnetic data may lead to the discovery of commercial structures in such areas, which, like large parts of Canada, are covered by several hundred feet of unconsolidated glacial drift.

The application of three-dimensional magnetic prospecting is liable to improve a great deal the chance of locating commercial structures magnetically. By publishing these vector maps, it is not so much the writer's intention, however, to draw renewed attention to the magnetic method at the expense of other geophysical methods, but rather to encourage magnetic investigations as a great help for the interpretation of results gained especially by the gravimetric and seismic methods. Both these methods work, as a rule, on beds considerably above the magnetically active horizons, and in many cases, only the combination of their data with the data gained magnetically from deeper strata will lead to a proper geological interpretation of the gravimetric and seismic indications obtained in a certain area.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934) PP. 106-118, 5 FIGS

GRANITE AND LIMESTONE VELOCITY DETERMINATIONS IN ARBUCKLE MOUNTAINS, OKLAHOMA[1]

B. B. WEATHERBY, W. T. BORN, and R. L. HARDING[2]
Tulsa, Oklahoma

ABSTRACT

Determinations of the velocity of elastic waves in the Tishomingo granite and Arbuckle limestone were made by seismic methods. The measurements on the granite were taken over both long and short spans in the same area, the former including distances of 500 to 2,500 feet, the latter, distances of 5 to 400 feet. Due to unusual precautions, the short-span data are accurate to 2 per cent. The long-span data give a straight line time-distance graph within observational errors and yield a value of 17,950 ft./sec. for the longitudinal wave velocity. The data taken over the shorter span show a definite curvature in the time-distance graphs, the longitudinal velocity varying from 14,880 to 17,150 feet per second, and the transverse velocity from 7,000 to 7,950 ft./sec. From these data the elastic constants of granite are calculated. Laboratory measurements were made on two small rods of granite from the same locality, by a method giving results accurate to less than 1 per cent. The velocities so obtained were somewhat higher. Velocity measurements were made along and across the bedding plane of Arbuckle limestone in a region where the dip of the bed approaches 90°. The velocity along the bedding plane was 17,400 feet per second and across the bedding plane 13,400 feet per second.

For some time the discrepancies between laboratory measurements of the elastic constants of rock samples and their measurements by seismic methods have been subject to discussion. At the present time, as far as the writers have been able to determine, there is no satisfactory explanation for this lack of agreement.

It was with the idea that an explanation might be found that the present work was undertaken. Two profiles were run on an extensive outcrop of the Tishomingo granite in the Arbuckle Mountains near Tishomingo, Oklahoma. Elastic waves, which were generated by explosions of dynamite, were recorded by an electrical seismograph, time and distance being the measured quantities. The first profile was started 500 feet from the shot point and was extended to 2,500 feet with the detectors placed at 200-foot intervals.

The time-distance graph for this profile is a straight line within the limit of error, which is considered to be 1 per cent. The velocity shown by this set of data for the longitudinal wave is 17,950 feet per second. Although impulses, which were probably due to transverse

[1] Read before the Geophysics Division of the Association at the Houston Meeting, March 24, 1933.

[2] Geophysical Research Corporation.

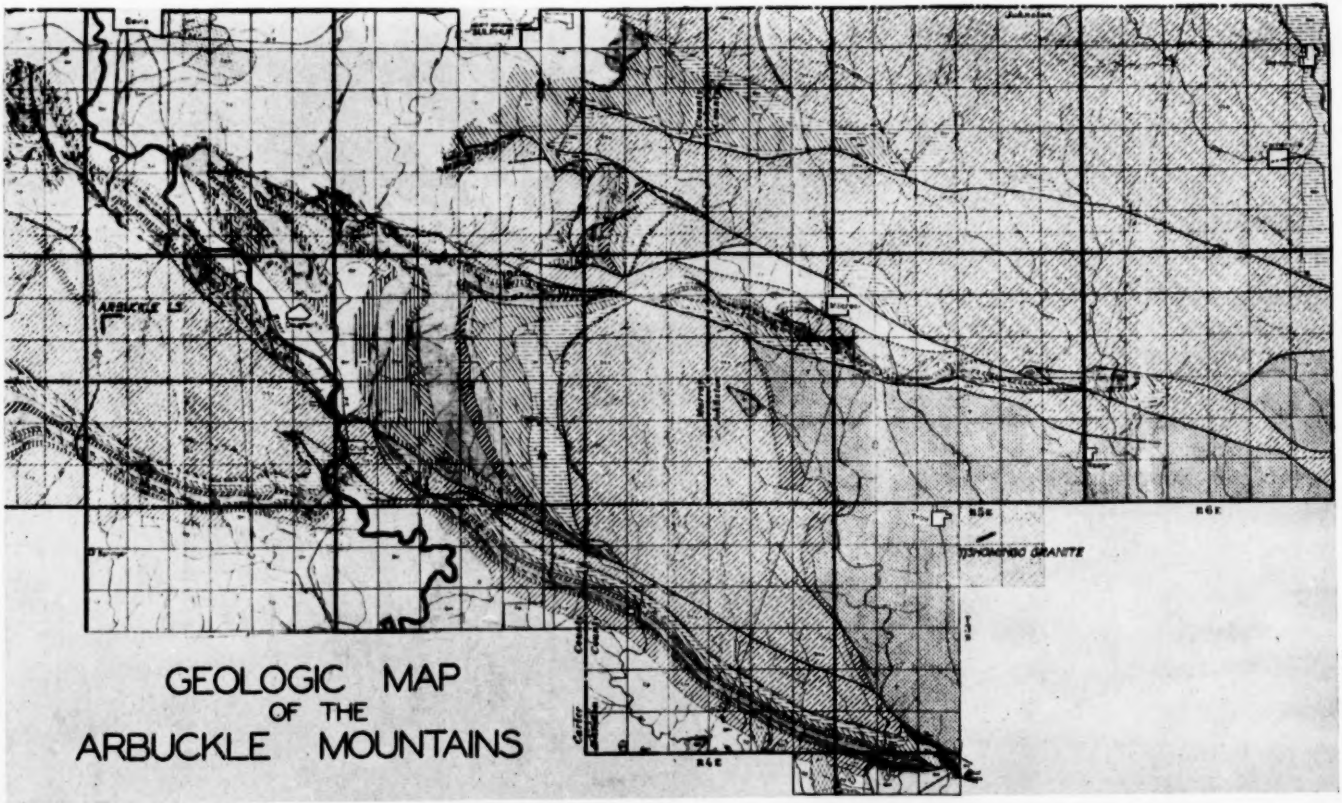


FIG. 1.—Geologic map of Arbuckle Mountains, showing recording locations. West-east distance, approximately 32 miles.

waves or Rayleigh waves, were observed on these records, they could not be interpreted with sufficient precision to draw any definite conclusions from them. Since it is necessary to obtain the transverse velocity in order to determine the elastic constants of the rocks by the seismic method, this profile shed no light on the problem.

The second profile, extending over a span of 400 feet, was laid out on a section of the granite which was free from fissures. The records taken over this profile showed both the longitudinal and transverse waves.

INSTRUMENTS

It was evident that it would be necessary to measure relatively small increments of time with a high degree of accuracy if a large number of points were to be obtained in this interval of 400 feet. If it be assumed, for the moment, that the velocity to be measured is of the order of 16,000 feet per second, and that the distance over which a velocity is to be determined be set at 100 feet, it would then be necessary to measure a time interval of the order of 0.0063 second. Since an accuracy of 2 per cent was desired, it was necessary to design recording and measuring instruments capable of detecting time differences as small as 0.00012 second.

The desired precision was attained by exercising extreme care in the selection of a perfectly matched set of detectors and recording channels.[3] The optical system was designed to give maximum sensitivity with a minimum width of the beam of light reflected from the galvanometer, thus producing a fine, clean-cut line on the record. The high frequency response of the recording systems was made as great as possible and a special fine-grain recording paper was used. The result was an extremely sharp, clean-cut, high amplitude break in the line corresponding with the time of arrival of the longitudinal energy. Time intervals of 0.01 second were placed on the record by means of an electrically driven tuning fork and a synchronized vibrating reed. This interval did not vary from an absolute value of 0.01 second by more than 0.04 of 1 per cent. Two complete sets of data were taken on this profile, one with a high speed oscillograph and the other using normal film speed. The purpose of the high film speed was primarily to obtain additional accuracy. The records were read with the aid of a micrometer microscope with which it was possible to read distances on the records corresponding to 0.00002 second.

[3] Theoretically this is not necessary where impulses corresponding with the first arrival of energy are observed. This added precaution was taken to insure uniformity in the later portions of the records.

METHODS

The section of granite selected for this work had a reasonably level and continuous surface for slightly more than 400 feet. No overburden of any sort was present.

A recording set-up comprising five detectors spaced 25 feet apart was placed at one end of this section of granite. It was found that it was quite essential to fasten the detectors rigidly to the granite since, when this was not done, relatively large errors were introduced by poor coupling. In order to accomplish this, plaster-of-Paris dams were built around the detectors and melted sulphur poured in. After the sulphur had solidified, the detectors were found to be cemented rigidly to the granite. Since it was necessary to use such extreme care in the mounting of the detectors, they were not moved during the course of the profile, but the shot point was moved instead. Shot points were placed every 100 feet, from 5 feet to 305 feet from the nearest detector. This gave data at 25-foot intervals, from 5 to 405 feet, with a check or overlap position on each record.

No indication of the instant of detonation was used in this work because of the possibility of small errors being introduced from this source. Times were measured from the instant of arrival of the wave to the nearest detector.

Two complete sets of data were taken on this profile. The first set was taken with a normal film speed in the oscillograph, that is with 0.01 second covering a distance on the record of about 0.75 centimeter. The second set was taken with a high film speed in the oscillograph, making the same time interval cover approximately 2.50 centimeters.

This procedure was carried out for both the longitudinal waves and the transverse waves. Separate sets of records were obtained for each type of wave. Specimens of the high and low speed longitudinal and transverse wave records are shown in Figure 2.

RESULTS

From an examination of Figure 3, it is seen that the time-distance graphs for both the longitudinal and transverse waves are slightly, but unmistakably, curved. If the observed points are plotted on a scale, of one half that shown in Figure 3, the graph then appears to be a straight line and it is only when an enlarged scale is used that the curvature becomes apparent.[4] From this it is evident that there is an

[4] Proof of the curvature of this line may be had by a least-square solution. Assuming a straight line, the residual is 0.00138 second while with the curve it becomes 0.00013 second.

increase in velocity with depth of penetration. As might be expected, the rate of change of velocity with depth is relatively small. From the curvature of the time-distance graph the penetration at 400 feet is estimated to be about 28 feet.

The longitudinal velocities calculated for four 100-foot sections of

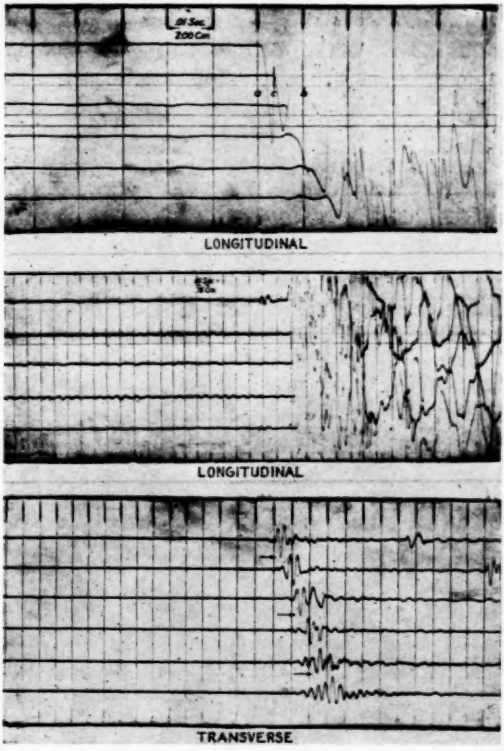


FIG. 2.—High and low speed longitudinal and transverse wave records.

this curve, range from 14,880 feet per second close to the shot point, to 17,150 feet per second at the far end of the curve. The corresponding transverse velocities are 7,000 feet per second and 7,950 feet per second. The longitudinal velocities are an average of 52 determinations; and the transverse, of 27 determinations.

The average density of the granite was obtained by determining

the density of a large number of samples taken from the rock in the vicinity of the location used. The average value so obtained is 2.65

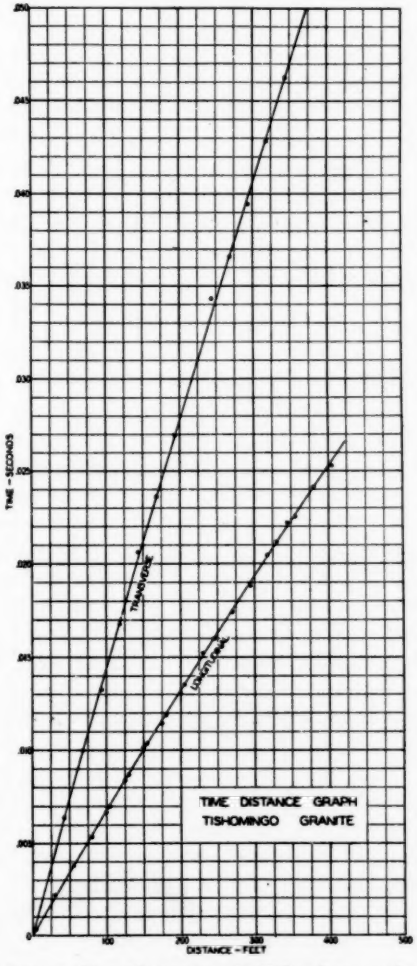


FIG. 3.—Time-distance graph, Tishomingo granite.

grams per cubic centimeter. Using this value, together with the observed velocities, the elastic constants may be calculated. The values thus obtained are shown in Table I.

TABLE I

		First Section 0–100 Feet	*Last Section 300–400 Feet*
Incompressibility	K	3.85×10^{11} dynes/cm².	5.17×10^{11} dynes/cm².
Rigidity	n	1.21×10^{11} dynes/cm².	1.56×10^{11} dynes/cm².
Compressibility	β	2.60×10^{-12} dynes/cm².	1.93×10^{-12} dynes/cm².
Poisson's ratio	σ	0.357	0.363
Young's modulus	E	3.29×10^{11} dynes/cm².	3.91×10^{11} dynes/cm².

Considering the fact that these values are representative of less penetration than the average values obtained by Leet and Ewing,[5] there is a remarkable agreement between their data and those presented here.

Although their average velocity values are somewhat higher, they are undoubtedly influenced by the high velocity portion of the time-distance curve since their profile extended to 4,000 feet.

SOURCES OF ERROR

In order to obtain an idea of the accuracy of the readings in this work, we may first consider the errors from a theoretical standpoint and then compare this with the observed variations.

Since the micrometer microscope makes possible the reading of distances on the records to 0.02 millimeter, and since the time interval measured (0.01 second) covered, on an average, 1 centimeter, a reading of a given point on the record could be made to 0.00002 second. In each determination of time, it was necessary to measure the two timing lines *a* and *b* and the instant of arrival of energy *c* (Fig. 2).

The maximum total error of reading would be obtained when the errors in all three readings were additive in the same direction and would therefore be .00006 second. However, it was not found possible to pick the instant of arrival *c* to this degree of precision. From an analysis of a large number of records it was concluded that the total error in picking the instant of arrival and in measuring the three necessary intervals on any one record did not exceed 0.00015 second. Since the total time corresponding with a distance of 100 feet is approximately 0.0063 second, the maximum error to be expected in reading any one trace would be approximately 2.5 per cent. In determining the average time for a given span a sufficiently large number of records were used so that the average value obtained is thought to be correct to within at least 2 per cent.

The distances along the profile used were laid out with a steel tape with a probable error negligible compared with the possible error made in measuring the time.

[5] L. Don Leet and W. Maurice Ewing, "Velocity of Elastic Waves in Granite," *Physics* (March, 1932), p. 160.

The frequency of the fork was maintained at 50 cycles per second within 0.03 per cent. The possible error in timing was therefore negligible.

Attention is directed to the fact that there are not as many supporting points on the time-distance graph of the transverse wave as there are on that of the longitudinal wave (Fig. 3). Due to the later arrival of the transverse energy in many cases there was interference between it and the longitudinal energy which made it difficult to pick corresponding points on successive traces. Consequently, only those traces were used where there appeared to be similar character. This is shown by the arrows on the transverse record of Figure 2.

LABORATORY MEASUREMENTS

Two samples of the granite were taken from this location for the purpose of making a laboratory determination of the velocity.

These samples were cut into two rods with a square cross section of 1.125 inches and lengths of 11.3 inches and 9.0 inches. A thin piece of steel was cemented to one end of the rod, which was supported by a clamp at its center. A permanent magnet around which a coil was wound was placed in line with the bar and near the steel on the end of the rod. The rod was then struck lightly on the opposite end, producing longitudinal vibrations which generated an E. M. F. of the same frequency in the coil. This E. M. F. and an E. M. F. from a calibrated vacuum tube oscillator were then impressed on the input of an amplifier, the output of which was rectified and the resulting beat frequency recorded. Then, this beat frequency and the frequency of the oscillator being known, the resonant frequency of the granite rod was determined. Substituting this value in the following equation gave the longitudinal rod velocity of the granite.

$$V = 2fl$$

Where V is the longitudinal rod velocity
f is the natural frequency
and l is the length of the bar.

Figure 4 shows specimens of records obtained by this method.

The density of these granite samples was determined by weighing them in air and in water. Knowing the longitudinal wave velocity in the rod and the density of the material, the value of Young's modulus may be found from the relationship

$$E = \rho V^2$$

Where E is Young's modulus
ρ is the density
and V is the longitudinal rod velocity.

Table II gives the values found for the two samples.

TABLE II

	Sample 1	*Sample 2*	*Average*
Dimensions	1.13 in. ×1.13 in. ×11.31 in.	1.13 in. ×1.13 in. ×9.0 in.	
Natural frequency	7,108 cycles/sec. (av.)	9,182 cycles/sec. (av.)	
Rod velocity	13,309 50 ft./sec.	13,773 100 ft./sec.	13,586 ft./sec.
Density	2.62 grams per cc.	2.68 grams per cc.	2.65 grams per cc.
Young's modulus	4.37×10^{11} dynes/cm.^{2}	4.72×10^{11} dynes/cm.^{2}	4.55×10^{11} dynes/c

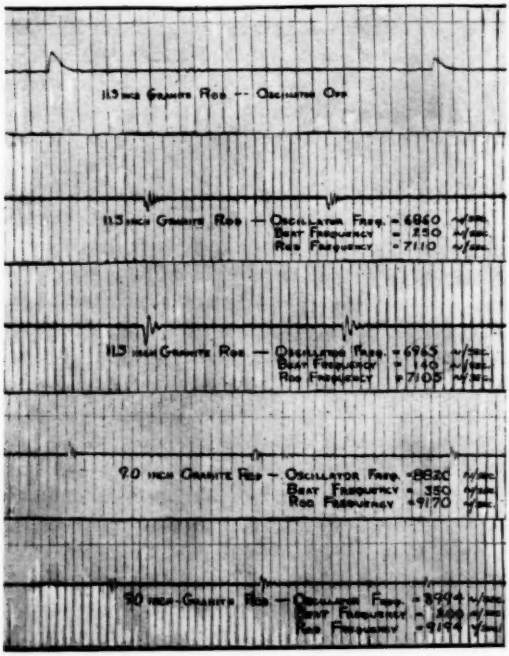


FIG. 4.—Records of beat frequency between electric oscillator and vibrating granite rod.

Young's modulus is the only elastic constant which may be directly obtained by this method. The longitudinal rod velocity observed is characteristic of the material in the form of a rod only, and is therefore not directly comparable with the bulk velocity determined in the field measurements. If, however, the value of Poisson's ratio for the material is known, the corresponding bulk velocity may be calculated by means of the relationship

$$V_{LB} = V_{LR} \sqrt{\frac{1-\sigma}{1-\sigma-2\sigma^2}}$$

Where V_{LB} is the longitudinal bulk velocity
V_{LR} is the longitudinal rod velocity
σ is Poisson's ratio.

By using the value of Poisson's ratio obtained in the field measurements, namely, 0.36, the bulk velocities for the two samples were calculated to be 17,380 feet per second and 17,900 feet per second, respectively, the average being 17,640 feet per second.

SOURCES OF ERROR

The most important error in determining the longitudinal velocity in the rods used was in the determination of the recorded beat frequency. The oscillator calibration was known to one part in 5,000 so that calibration errors were negligible. The lengths of the rod samples were easily measured with sufficient accuracy so that any error thus introduced could also be neglected.

The equation relating the natural frequency of the rod to its length and the velocity of sound in the material is strictly accurate only if the length of the sample be very large compared with its lateral dimensions. In the case of relatively short rods, a correction must be applied to the experimentally determined value of natural frequency. The expression for this correction has been derived by Lord Rayleigh.[6] This correction was calculated for the particular samples used and was found to be considerably less than the experimental errors and so was neglected altogether.

The total error in the determination of the rod velocity of any particular sample was less than 1 per cent.

The temperature coefficient of frequency of the rock samples was not determined. The measurements were made at a temperature of 23° C.

COMPARISON OF FIELD AND LABORATORY DATA

The average bulk velocity for the longitudinal wave calculated from the laboratory data, namely, 17,640 feet per second, corresponds with the value of 17,950 feet per second observed over the long profile used in the field work and corresponds reasonably well with the value of 17,150 feet per second obtained for the 300 to 400-foot interval of the shot profile. To this extent, at least, the laboratory and field determinations may be said to agree. The values of Young's modulus obtained by the two methods do not, however, show any such agreement. Furthermore, the velocity of 14,880 feet per second characteristic of the 100-to-200-foot interval of the short field profile is de-

[6] Lord Rayleigh, *Theory of Sound*, Vol. 1, p. 251.

cidedly at variance with the velocity determined by the laboratory methods. It might reasonably be expected that the velocity in a small sample which is under no external pressure should check the velocity found for granite near the surface rather than that of the granite at some depth. It must be concluded, therefore, that there is a serious discrepancy between the two sets of data, which can not be accounted for by the experimental errors inherent in either method. The question, therefore, arises whether there is some factor influencing the results obtained by the laboratory method which does not affect the results obtained in field measurements. This point has been rather carefully investigated, but will be discussed only briefly.

One decided difference between the velocity measurements made in the field and those made in the laboratory is in the frequency used in making the measurements. The frequencies recorded in the field are approximately 100 cycles per second, while the natural frequencies of the rock samples tested in the laboratory are about 7,000 cycles per second. The question arises whether there is sufficient variation of velocity with frequency to account for a difference in the results obtained in the two cases. One possible effect which might cause a change of velocity with frequency is due to the fact that the attenuation constant of an elastic solid is a function of the frequency, and that the velocity at any frequency is dependent, to some extent, on the value of the attenuation constant.

The effect of attenuation upon the velocity may be disposed of very briefly. It may be shown that, if the attenuation in the rock sample under test is sufficiently low to permit the sample to oscillate vigorously enough to make the laboratory method practicable, then the effect of the attenuation upon the velocity will be negligible.

Another factor which might affect the results is the different amplitudes used in the two methods. Little information is available concerning the propagation of disturbances of finite amplitude in solids. It is believed, however, that the amplitudes used in both field and laboratory measurements are in general small enough so that the velocity is independent of the amplitude. The amplitudes in both cases are estimated to be of the order 10^{-6} cm. although, in the case of field measurements, the amplitude may be considerably larger at points near the shot point. A qualitative idea of the magnitude of the effect for this order of amplitude can be obtained by making use of the formula applicable to the transmission of plane waves of finite amplitude through gases. These calculations indicate that for the case assumed, the effect is entirely negligible. Calculation further shows that the amplitude would need to be of the order of 10^{-3} cm. to produce a

variation in velocity of even 0.10 per cent. This effect may, therefore, also be neglected.

If, therefore, the samples used in making the laboratory determinations are truly representative of the bulk of the material in which the velocity is determined in the field, the results obtained in each case should be directly comparable, and the lack of agreement must, therefore, be interpreted as being due to an actual difference in the elastic constants of the samples used and the average value of those of the rock *in situ*. In the present investigation only two samples of the granite were used in making the laboratory determinations so that the "sampling error" may have been large. There is a further possibility that the elastic constants of the small samples may differ from those characteristic of the material before being cut out.

Another probable cause of the observed difference is a possible variation in the moisture content of the granite *in situ* and that of the samples used in the laboratory work. Recent work of the authors has shown that the presence of a small amount of moisture may seriously affect the elastic constants of rocks. This effect has also recently been reported by W. A. Zisman.[7]

Preliminary work by the writers indicates that the presence of moisture, in general, lowers the value of Young's modulus. The lower value of Young's modulus observed in the field determinations may, therefore, be due, in part at least, to larger percentage of moisture in the surface granite in the field as compared with that in the laboratory samples. Although no effort was made to dry out the samples used in the laboratory work, they were actually in an air-dry condition.

It is interesting to note that this explanation serves also as a possible explanation for the unexpectedly large curvature of the time-distance graph obtained from the field data. The increase of velocity with depth may prove to be partially due to a decrease in the moisture content of the rock below the surface.

Work is now in progress to test the validity of the explanations here advanced and it is hoped that they may be reported later.

ARBUCKLE LIMESTONE

Two profiles were laid out in the Arbuckle limestone with distances of 100–2,500 feet from the shot point. Detectors were placed every 200 feet along these spreads. A section of the limestone outcrop where the angle of dip of the bedding planes was approximately 90° was selected for the work. The lines of the two profiles were at right

[7] "Elastic Constants of Rocks and Their Relation to Seismic Wave Speeds," *Physical Review*, Vol. 43, p. 501.

angles to each other so that one set of data was taken along the bedding plane and the other across the bedding plane.

The time-distance graphs (Fig. 5) of these two profiles were drawn as straight lines since the accuracy of the data was not great enough to determine penetration.

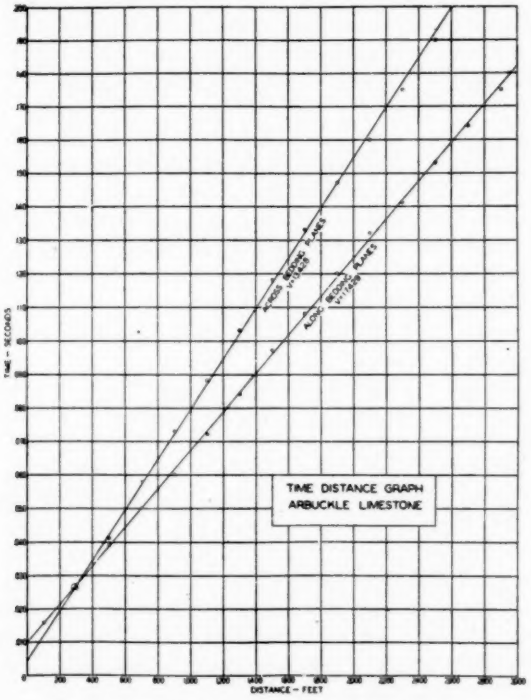


FIG. 5.—Time-distance graph, Arbuckle limestone.

The average velocity across the bedding planes of the limestone was found to be 13,430 feet per second and the velocity along the bedding plane was found to be 17,430 feet per second.

These results are in agreement with the data presented by McCollum and Snell.[8]

In conclusion, the writers wish to express their thanks to E. E. Blondeau and L. Y. Faust for their assistance in calculating and checking the data.

[8] Burton McCollum and F. A. Snell, "Asymmetry of Sound Velocity in Stratified Formations," *Physics* (March, 1932), p. 174.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 119-132). 5 FIGS.

APPLICATIONS AND LIMITATIONS OF DIP SHOOTING[1]

E. E. ROSAIRE[2] and JOSEPH L. ADLER[3]
Houston, Texas, and Houghton, Michigan

ABSTRACT

The history and methods of dip-shooting are outlined and the degree of accuracy obtainable by the method is investigated. Plotting of the misclosures on 151 dip-shooting traverses in the Gulf Coast to yield a frequency curve shows a probable error of about 87 feet, in traverses averaging 27,500 feet in length. This error is apparently independent of the length of the traverse, and within the range of spreads commonly used, that is, from 1,400 to 2,400 feet, independent of the spacing of the dip determinations. The smoothness of the frequency curve is broken by an excessive number of misclosures greater than 250 feet. These may be due to unusual structural conditions on the traverses concerned, such as terracing between dip points or faulting, or to gross personal errors. The principal common errors appear to lie in the drafting of the profiles, the determination of the time step-out, and the weathering correction. These errors on individual dips may considerably exceed the probable error, but on traverses of average length will tend to compensate one another. Other sources of error are discussed, but are believed to be of minor importance.

The purpose of this paper is to present an outline of the methods used in the determination of the dip of sound-reflecting strata in the Coastal Plain series of Louisiana and Texas by the reflection seismograph, and an analysis of the errors involved. Many data accumulated by Rosaire and Kannenstine and the Independent Exploration Company, of Houston, were available for this purpose. Especial acknowledgement must be made to J. D. Marr and C. B. Bazzoni for suggestions bearing on the research.

CONDITIONS GOVERNING CHOICE OF METHOD

The fundamental limitation on the use of reflections is that in themselves they tell little or nothing with regard to the nature of the reflector. Even in the "hard rock" areas, where definite lithological breaks occur, reflections must be identified by some auxiliary method, such as checking against the log of a well already drilled, or preferably, determining arrival half time by recording or shooting down a well.

In the upper portion of the Coastal Plain series no laterally persistent lithologic horizons have yet been determined, and so, *a priori*,

[1] Read before the Geophysics Division of the Association at the Houston meeting March 24, 1933. Manuscript received, September 30, 1933.

[2] Rosaire and Kannenstine, consulting geophysicists, Houston, Texas.

[3] Assistant professor of geology, Michigan College of Mining and Technology, Houghton, Michigan.

correlation of reflection depths holds forth little promise as a method of procedure in areas where oil production is sought from these strata. As a general rule, records of the reflections in these beds from two near-by shot points show little or no correspondence of reflection events. Records from adjacent shot points are no more correlatable than average well logs in those areas. In areas where the lower Tertiary is within reach of the drill, however, as on the so-called Conroe trend, it is sometimes possible to match reflections, and to contour depths on some persistent reflecting horizon with a considerable degree of confidence.

On the other hand, the salt-dome province of the Gulf Coast is in general characterized by localized structures of great relief. As a rule, there is very little surface topography, and the surface aerated layer is generally thin and uniform. Finally, the average velocity down through the geological column is a minimum, as compared with that of the Mid-Continent. All of these factors favor the accurate determination and use of the dip of the reflecting beds in mapping structure, a method which at present seems to be the one which holds the greatest promise for detailing sedimentary structure above the more deeply buried salt domes.

CORRELATION METHODS IN REFLECTION SURVEYS

Several investigators prior to 1926 had experimented in the use of reflections, but the general use of the method at present is undoubtedly closely associated with the success of the methods developed by the Geophysical Research Corporation.

This work was initiated in 1926 by J. E. Duncan, on the Nash salt dome in Fort Bend County under the supervision of J. C. Karcher. He continued his efforts there and in other areas in the Gulf Coast and in the Balcones fault zone, although his success was only promising, to say the least. However, due both to accumulated experience and perhaps to the chance to work on better defined problems, his results improved as he moved back into the hard-rock country, until he was getting fair reflections from the Viola limestone at Seminole. During the following two years, the Geophysical Research Corporation, in conjunction with the Amerada Petroleum Corporation, steadily worked on the problem, with regular improvements in technique. To-day's reflection technique is essentially that developed by the Geophysical Research Corporation during these two years, and on the whole, the use of dip shooting is really the only new departure from the interpretation methods established in Oklahoma from 1927 to 1929.

In justice to the investigators and their sponsors, the writers feel that some attention must be called to the fact that many scientists holding responsible positions in companies sponsoring major geophysical programs, refused flatly to admit that the method was based on fact. As one who personally tried to introduce the method into general consulting practice, the senior writer can definitely recall many times when reflections were not even considered on a par with the divining rod, for at least that device had a background of tradition.

DIP METHODS

In 1929, with the end of refraction explorations in sight, Eugene McDermott, then of the Geophysical Research Corporation, secured the approval of L. P. Garrett of the Gulf Production Company, to try reflections in the Gulf Coast. It must be admitted that no interpretation other than that developed in Oklahoma was contemplated, that is, the correlation of reflections from supposedly consistent beds. Some success was secured on two producing domes, Hankamer and Port Barre, but the method failed at the Clodine Prospect, and one dry hole was credited there to attempted correlations.

The next trial was at Darrow, then considered a very favorable refraction discovery which had been confirmed by the torsion balance. However, the area had already been investigated by two wells, both dry. So where even geologists walked softly, a reflection survey was started.

T. I. Harkins, in charge of the work, noticed that abnormal step-outs in the reflection time were rather characteristic of the area, and that these abnormal step-outs reversed. He correctly attributed this phenomenon to dipping beds, and pointed out that when recording up-dip the reflection arrival times for the farthest geophone should be abnormally short, and when recording down-dip they should be abnormally long. The method was then placed on a more quantitative basis, and is now the recognized method for mapping the younger formations of the Gulf Coast.

Since that time, the method has had some striking successes, and also some disappointments. However, these disappointments were largely the result of condemning reflection structures with single drill tests, which, to say the least, is somewhat rigorous. However, the background of success is rather satisfactory, since in several instances the reflection detail resulted in the location of discovery wells even after as many as three dry holes had supposedly condemned a prospect. On the other hand, at least three prospects have been drilled in spite of a condemnation by reflections, with resulting dry holes.

COMPUTATION OF SUBSURFACE DIP FROM REFLECTIONS

Figure 1 illustrates how dips are measured by reflections. By plotting the image of the shot point for the recording geophones, the problem is resolved into one of triangulation upon this image point by means of sound-wave paths. The distance between the recording geophones serves as a base line, and the other two sides of the triangle are the path lengths of the recorded reflections. Since only the travel times for these reflections are determined directly, the triangle is completed by multiplying these travel times by the appropriate velocity with which the sound waves have traveled. This computation is

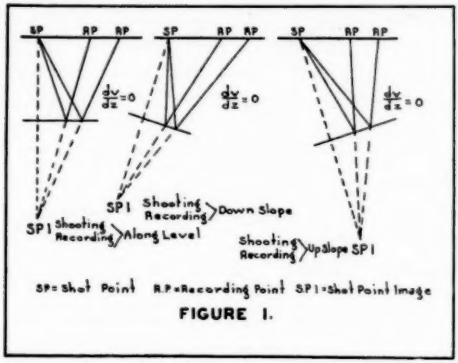


FIG. 1.—Geometrical solution of dip determination.

modified by certain corrections necessitated by a thin zone of low-velocity material almost invariably present at the earth's surface. The methods of correcting for this zone, known as the "aerated layer," are familiar to seismologists, but are too involved to describe here.

The velocity of the sound waves below the aerated layer can be measured in any of several ways. One method is to lower a recorder down a well, and record the travel time from an explosion at the surface. A second method is the analysis of refraction data from a profile of appropriate length and recorder density. Thirdly, the appropriate velocity may also be determined empirically by an analysis of the reflection times themselves, and due to the general lack of available refraction profiles or well recordings, this is the most widely used method in the Gulf Coast.

ACCURACY AND CONTROL

Dip reflection surveys for the purpose of local preliminary reconnaissance consist essentially of unclosed traverses, in general made up

of straight lines intersecting approximately at the center of interest. This was the first type of survey originated, and is still used by many operators.

Shot points and recording positions alternate along some convenient straight line, so that records are taken on each geophone position from adjacent shot points. Using an appropriate velocity, the individual reflections are plotted on a one-one scale. After beginning at some convenient depth the profile of a "phantom" horizon is projected by use of the dips from near-by reflections. The elevations of this horizon are carried from one profile to another at the points where the traverses intersect, and the even hundred-foot elevations of the horizon are spotted on a map. By use of a contour interval of approximately 100 feet, the structure is then contoured on the resulting phantom horizon.

Such a survey is simple, and rarely leads to complications in interpretation, since with no closing traverses any error simply results in freak contouring. A simple survey of this type is quite satisfactory for symmetrical, unfaulted structure.

While, as pointed out later, errors inherent in the dip method tend to cancel each other over large areas, for accurate detail small closed traverses must be used, and the error in each must be distributed around it. We have therefore borrowed the torsion-balance technique, such as described by Roman.[4] This distribution of the apparent errors must precede any attempt at contouring. It can generally be made by inspection, or the whole traverse least squared by any one of a number of methods developed for use in torsion-balance surveys.

STATISTICAL ANALYSIS OF ERRORS

One hundred fifty-one closed traverses shot by the dip-reflection method, having a total length of 786 miles and involving 2,458 dip determinations, were used for the investigation. On these traverses the difference in elevation of an ephemeral horizon had, in large part, already been computed from the dips. The differences in elevation were summed up in a clockwise direction. An increase of elevation in that direction was given a positive sign, a decrease a negative sign. The residual found on closing the traverse has been termed the "misclosure." It is designated in feet and carries the sign resulting from an algebraic addition of the differences in elevation around the traverse.

The misclosure of each of the traverses used has been plotted with-

[4] Irwin Roman, "Least Squares in Practical Geophysics," *Geophysical Prospecting* (1932), p. 491.

out regard to sign to obtain the misclosure frequency curves reproduced in Figure 2. The number of occurrences of each misclosure has been laid off vertically. The amount of the misclosure to the nearest 10 feet is indicated along the horizontal axis.

A radical break in the original irregular curve will be noted at about 250 feet. This break may indicate that the errors in excess of 250 feet, which are obviously more frequent than errors near 250, are due to some special conditions or to gross personal errors occurring on a few traverses. The nature of such special conditions is discussed later, but it may be said here that they are probably geological.

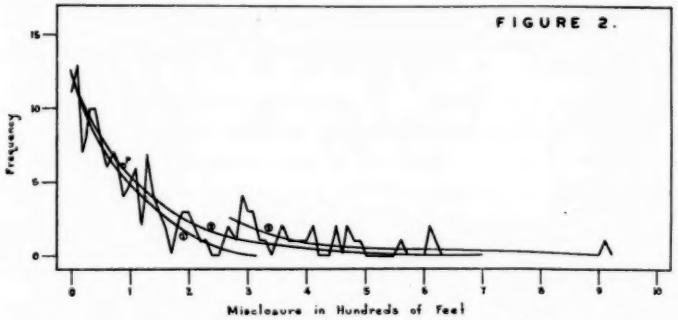


FIG. 2.—Frequency curve showing misclosure on 151 traverses. Horizontal co-ordinate of point P equals probable error.

To bring out this break, separate curves, numbered 1 and 3, have been fitted to the two portions of the original curve. Curve 1 may indicate the frequency of the usual errors encountered in dip shooting, while curve 3 may indicate in part the frequency of large errors due to special conditions. If that is the case, it would be advisable for the geophysicist to investigate any misclosure in excess of 250 feet which he may encounter in the course of his work, to discover if some peculiar geological condition such as faulting or terracing is not present. It may be, however, that the break noted in the curve is simply an accident due to insufficiency of data.

Curve 2 is an exponential curve representing the mean of curves 1 and 3. It approximates very closely the curve best fitting the original data. It is, moreover, capable of formulation as follows.

Equation (1) $x = 3.1 - 1.23 \log y$ where x equals the misclosure in hundreds of feet and y equals the frequency of occurrence.

From this equation the probable error in the traverses analyzed may be computed. The probable error has been defined as "that error

which in a large number of cases is as often exceeded as not." Since the area under curve 2 is directly proportional to the number of cases considered, the value of the horizontal co-ordinate (x) corresponding with half the total area will be the value of the probable error. This value was found to be about 87 feet. The mathematical solution of the problem follows.

Differentiating equation (1), we obtain

Equation (2) $dx = -1.23\ (d \log y) = -1.23\ dy/y$

The area under the curve is the integral of ydx. As, by equation (2), dx equals $-1.23\ dy/y$, we have for the area A

Equation (3) $A = -1.23 \int_0^\infty y dy/y = -1.23\ (y_\infty - y_0)$

By equation (1) when x is equal to zero

Equation (4) $0 = 3.1 - 1.23 \log y$

(5) $\log y = 3.1/1.23$

(6) $y = e^{2.64} = 12.3$

Again by equation (1), when x is equal to ,

Equation (7) $\infty = 3.1 - 1.23 \log y$

(8) $$\log y = \frac{3.1 - \infty}{1.23} = -\infty$$

(9) $y = e^{-\infty} = 0$

Then by equations (3), (6), and (9), we have

Equation (10) $A = -1.23\ (y_\infty - y_0) = -1.23\ (0 - 12.3) = 15.1$

But the probable error is that value of x corresponding with half of the area, A. Let us designate this value of x as p. Then, substituting 7.55 for $1/2\ A$, y_p for y_0, and zero for y_∞ in equation (3) we derive

Equation (11) $7.55 = -1.23\ (0 - y_p) = 1.23\ y_p$

(12) $y_p = 6.14$

Substituting p for x and 6.14 for y_p in equation (1), we find,

(12) $p = 3.1 - 1.23 \log 6.14 = 0.87$

As this is the probable error sought, expressed in hundreds of feet, the probable misclosure deduced from the available data is about 87 feet.

The probable error or misclosure here computed will serve as a measure of the accuracy to be expected from the dip-reflection method in the Coastal Plain series on the Gulf Coast. Some of the sources of misclosure, together with the conditions affecting the accuracy of the dip method will be considered next.

CRITICAL ANALYSIS OF METHODIC ERRORS

Probably the greatest source of error is in the drawing of profiles. The average length of the traverses in the group considered was 27,500 feet. Dividing the probable misclosure by the average length of traverse we obtain the tangent of the probable angular misclosure, the net error being distributed over the entire length of the traverse.

$$87/27{,}500 = 0.00316 = \tan 0°.11'$$

This angular error is astoundingly small. Clearly in making up a

profile a computer can not plot the dips to so great a degree of accuracy. Indeed, the difference between the dips of the several reflections obtained at different horizons from the same shot is usually several times this amount. In drawing the phantom horizon, however, the geophysicist, realizing which dips conform best to the structural picture he is making, will naturally select those yielding the least misclosure. This personal element doubtless accounts to some extent for the surprisingly small value of the probable error; but it must also be remembered that the error here determined takes into account the compensatory effect of numerous observations.

Another considerable error may enter into the computation of the dips through incorrect time determinations. Such errors may be due either to phase lag in the recording instrument, or to the personal element in picking the exact time on the record. Errors of more than 0.002 second due to these two causes are probably not unusual,[5] and might produce errors in the time difference of at least 0.0015 second. While such an error in determining the time step-out would produce an error in dip of more than 1°, the compensatory effect of the numerous observations made in any traverse will reduce the net error to a fraction of this amount.[6]

Other sources of error dependent upon inaccuracies of measurement lie in the determination of the thickness of the low velocity zone under the first and last geophones, computations based on an incorrect velocity for that zone, and use of an incorrect velocity in the underlying high-velocity zone. Of these three sources of error, the first is the most serious. Where great variability in the thickness of the low velocity zone exists, its relative thickness under each of the end seismometers must be determined as accurately as possible before any validity can be attached to the dips computed. A difference of 3.5 feet in the thickness of the low-velocity zone between the ends of the geophone spread may easily produce an error of about 1° in the computed dip if not properly corrected.

Errors in the velocity itself are less important. While the use of an erroneous velocity may produce an error in dip of several degrees, since shot points are located at equal distances on opposite sides of the seismometer position, the errors will be in opposite directions in the pair of dips so obtained from each reflecting horizon. They thus compensate each other almost exactly. If the error is great this alterna-

[5] C. B. Bazzoni, personal communication.

[6] Paul Weaver, paper read before the Houston Geological Society, September 21, 1933.

tion of direction becomes obvious in the profile and the velocity may be corrected accordingly. The phenomenon of alternate opposite errors in dip is commonly known as "wash-boarding."

A more serious velocity error enters where there is a rapid but uniform change of velocity horizontally. This results in a displacement of the image point in the direction of increasing velocity. In consequence, the computed dip of the sediments will be rotated downward away from the direction of increasing velocity, as compared with the true dip. Therefore, if the velocity in the sediments over a deeply buried salt dome increases over the uplift, the uncorrected dip picture will tend to exaggerate the structure. Refraction surveys have demonstrated that many of the more deeply buried domes produce such velocity increases in the overlying sediments, as at Iowa.

This type of velocity change will produce "wash-boarding" in those portions of the area where the velocities are notably different from the standard velocities used for various depths. But the error here referred to will not be compensated by the "wash-boarding," as it always rotates the dip downward away from the direction of increasing velocity, regardless of the direction of the shot.

In dip shooting it is assumed that the plane of the incident and reflected wave-path is vertical. Obviously, this is true only when the shot point and seismometers are lined up directly along the direction of dip. If they are lined up in any other direction the plane of the wave path lies not vertical but at right angles to the reflecting bed. The dip measured is then the component of the dip in that plane rather than in a vertical plane. The error introduced by this inclination of the reflection plane, generally known as "side-swipe," is negligible in the case of low dips, but where the dip is steep and the strike variable, it might produce a perceptible misclosure. This would be especially likely if the form of the closed traverse departed far from a parallelogram. In that case the errors made by shooting diagonally across the dip downward would not be compensated in shooting diagonally across the dip upward on the opposite side of the traverse, or *vice versa*.

A factor which might be expected to control the amount of misclosure is the spacing of the dip determinations. In drawing an ephemeral horizon the dip between the points where it has actually been determined must be interpolated. This interpolation is, of course, based on the assumption that no radical variations in dip occur between the actual determinations. This assumption is obviously a possible source of misclosure, and accordingly, closer spacing of dips should tend to reduce misclosure.

The writers attempted to ascertain whether the spacing factor exercised any control over the amount of misclosure in the traverses analyzed. The average spacing of dips on these traverses varied from 1,400 to 2,400 feet, with a very few lying outside of this range. For 107 of the traverses, selected at random, the amount of misclosure was plotted along the horizontal axis of a graph, while the average spacing of dip determinations in the same traverse was laid off vertically. The resulting diagram is shown in Figure 3.

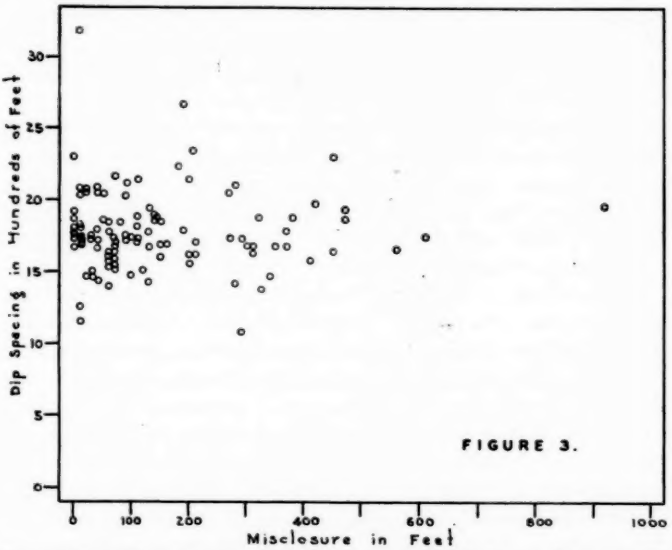


FIG. 3.—Comparison of average spacing of dips with misclosure of traverse. Chart shows no apparent relationship.

An inspection of the figure reveals a scattering of points through which no mean curve could justifiably be drawn. This negative result is probably explainable by the lack of variety in the several traverses considered. It serves to demonstrate, however, that for the dip spacing used in the work analyzed, the spacing exercised little if any effect on the amount of misclosure. Considering also the surprisingly small size of the probable angular misclosure obtained, this result suggests that no closer spacing is necessary, and indeed, that an even wider spread than the average one used might be practicable. The average spread on the traverses studied from the shot point to the middle geophone was 1,700 feet.

It has already been pointed out that due to the custom of transmitting the seismic waves in alternate directions around the traverse most of the errors discussed tend to cancel on alternate shots. A careful tabulation of the direction of shooting on the traverses inspected showed an almost equal distribution of the alternate directions around each traverse. Only the effect of "side-swipe" on asymmetrical traverses and rapid horizontal increase of velocity over deep salt domes seem likely to produce cumulative errors.

Cumulative errors should on the average produce maximum mis-

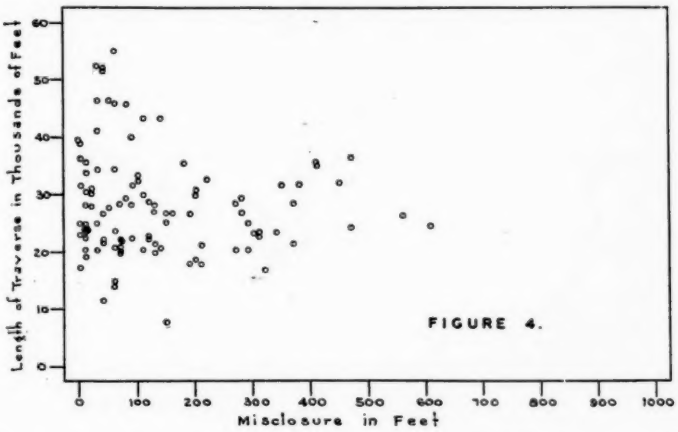


FIG. 4.—Comparison of length of traverse with amount of misclosure. Chart shows no apparent relationship.

closure on the longest traverses, while non-cumulative errors should tend to balance out more perfectly on the longer traverses. The same 107 traverses shown in Figure 3 were plotted to yield Figure 4. In the latter figure the amount of misclosure of each traverse has been laid off along the horizontal axis while the length of the traverse has been laid off vertically. An inspection of the figure shows a scattering of points indicating no readily perceptible relation between the length of the traverse and the amount of misclosure. It is therefore concluded that cumulative errors enter but slightly into the dip-reflection method, and that the length of the traverse has little to do with the amount of misclosure, except for the cases where the misclosure should be explained as follows.

STRUCTURAL SIGNIFICANCE OF LARGE MISCLOSURES

The most significant source of misclosure will, of course, be sought in structural conditions. We have seen, however, that only in cases of extreme misclosure, namely misclosures in excess of 250 feet, is it necessary to seek such a source. One structural condition which would readily give misclosure is a short sharp divergence from the normal dip, producing in effect a small structural terrace. Such a dip might yield a reflection on one side of a closed traverse and, due to the accident of dip spacing, fail to be detected where crossed by the other side of the traverse. Or the terrace might die out laterally and therefore intersect the traverse at one place only. In the latter case a large misclosure would result if no reflection were observed upon the terrace.

Another structural source of large misclosure may be the intersection of the traverse by a fault at one point only, the fault terminating somewhere within the traverse. Likewise a fault that continues across both sides of a traverse will produce misclosure if its throw differs markedly at the two points of intersection. In either case the fault must necessarily be of the hinge type. A fault having approximately equal displacement at its two points of intersection with the traverse cannot produce a misclosure large enough to be safely attributed to structural conditions.

In postulating faulting as the explanation of a large misclosure, due consideration must be given to the limitations set by common geological knowledge of the behavior of hinge faults. While there is, of course, some change in the rate of decrease of displacement in passing from the point of maximum displacement toward either end of the fault, this change in rate is very gradual. Consequently, large misclosures caused by hinge faulting should be observed on several adjoining traverse blocks, should differ more or less uniformly in value, and except where passing over the point of maximum displacement, should be of like arithmetical magnitude. In passing over the point of maximum displacement, however, the sign of the misclosure will change.

If the observer places himself on the upthrown side, faces the fault, sums up the changes in elevation around the traverses in a clockwise direction, giving a positive sign to increases in elevation and a negative sign to decreases, the following rule will apply: positive misclosures will lie on the right of the point of maximum displacement; negative misclosures will lie on the left. By means of this rule the upthrown and downthrown sides of the fault may be distinguished.

This rule may be used only where the point of maximum displacement lies within the area under examination. If the fault dies out within the area prospected the upthrown side may be distinguished by the following rule. If the observer places himself on the downthrown side of the fault, facing the fault, positive misclosures in the successive traverses which the fault cuts will increase toward the right, while negative misclosures will increase toward the left. If neither the end nor the point of maximum displacement of the fault lies within the traversed areas, the direction of throw can not be determined, as the points of maximum positive and negative misclosure lie approximately

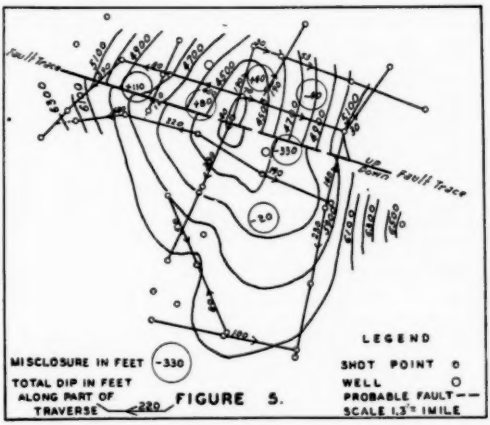


FIG. 5.—Structure contour map of faulted salt dome showing effect of differential displacement on closure of traverses. Contour elevations below sea-level.

midway between the point of maximum displacement and the ends of the fault. Therefore the misclosures will all be of like sign in the case postulated, and the amount of misclosure will decrease either toward the end of the fault, or toward the point of maximum displacement, or both, the two directions being indistinguishable under the circumstances.

In all of the work examined only two cases of misclosure which the writers considered justifiably attributable to faulting were found. One of these cases is used here as an illustration of the principles already outlined. A portion of the structure-contour map built up on dip-reflection data is shown in Figure 5. The significant closed traverses are also given, and the amount of misclosure is written in the center of each. The fault was first suspected because of the progressive values

of the misclosure in the three traverses through which it is believed to pass. These are from west to east, plus 110 feet, plus 80 feet, minus 330 feet, suggesting a fault having its maximum displacement near the common side of the eastern and middle traverses and its upthrown side on the north.

Paleontological data and lithological logs from two wells, one on each side of the supposed fault, appear to indicate a maximum throw of about 1,200 feet. As the paleontological markers used have not been thoroughly tested in the region, however, this amount of throw may be erroneous. The horizon used was a calcareous bed characterized by the simultaneous first appearance of *Textularia mayori* and *Nonion scapha* in one well, and in the other well the simultaneous first appearance of the same two species in shale a little more than 30 feet below it. No species whatever of *Textularia* or *Nonion* were found above this horizon in either well. Correlated on the basis of the calcareous bed referred to, a good correspondence between the principal calcareous and sandy horizons in the lithologic logs of the two wells was found.

The two faults noted by the writers in the course of the research were rendered conspicuous by the large misclosures they produced on some of the traverses they crossed. Faults with less differential of displacement would easily pass unnoticed because of the small misclosure they produce. In conclusion, therefore, it may be said that faults having small differential of displacement will go undetected in dip-reflection work and may constitute one of its greatest sources of error.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 133-142, 3 FIGS.

GEOLOGICAL NOTES

CORRECTIONS FOR TEMPERATURE IN BAROMETRIC SURVEYING

Because a column of air of a given height is lighter if the air is warm than if it is cold, and because an aneroid barometer, in effect, measures the weight of a column of air corresponding in height with the difference in elevation between successive stations, accurate barometric surveying can not be done without correction for temperature unless the terrain has very low relief or the temperature is close to 50°F., for which most barometers are calibrated.

The makers of barometers generally state that their instruments are compensated for temperature. This does not mean, however, that the temperature correction need not be applied—it means only that the instrument is compensated for errors within its own mechanism due to expansion or contraction of the metal.

The amount of the necessary temperature correction is approximately two tenths per cent (0.2039)[1] per degree Fahrenheit above or below the temperature for which the instrument is calibrated (generally 50°F.). If the temperature is above 50° the instrument will indicate too small a difference in elevation between two stations, and the correction must, therefore, be added. If the temperature is below 50°, the correction must be subtracted from the indicated difference in elevation.

Probably most barometric surveying is done in summer, and much of it when the temperature ranges between 80° and 100°F. At such temperatures, failure to make the temperature correction will cause serious errors. Where the relief is 50 feet or less, the correction may sometimes be neglected, but in careful work with the better instruments, corrections should always be made where the relief is greater than that amount. For even moderately high relief the error becomes serious if correction is not made—22 feet, for example, for a relief of 300 feet and 35 feet for 500 feet if the temperature is 85°.

METHOD OF MAKING TEMPERATURE CORRECTIONS

A method of making the necessary temperature corrections in connection with systematic barometric surveying has been published

[1] Raymond A. Hill, *Preliminary Survey Procedure* (American Paulin System, Inc., Los Angeles, California, 1929).

by Hill[2] and by Lahee.[3] According to this method, the correction is made for the difference in elevation between each two stations and the algebraic sum of these corrections is carried forward from station to station.

For several years the writer has used a different method that seems to him to be simpler and less time-consuming in its application than that described by Hill and Lahee and is not subject to cumulative error which might readily occur in the other method either through carrying from station to station the algebraic sum of the temperature corrections when these do not come out in even numbers

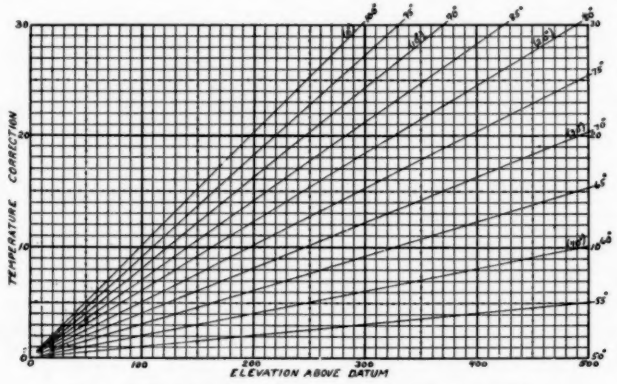


FIG. 1.—Chart for determination of temperature corrections.

of feet, or through a mistake in the computation for any one station, which would automatically be carried on through all other stations to the next checking point. The method has been used mainly in a region of moderate relief and is most useful in such areas. For high relief, where differences in temperature between valley bottoms and hill tops is considerable, the method described by Hill and Lahee is probably preferable.

The essence of the plan is to make temperature corrections for all readings with respect to a common datum plane which, in practice, is generally the next even hundred feet below the valley bottoms of the district to be surveyed. If, for instance, the major streams of a region lie between 500 and 600 feet above sea-level, the datum chosen would be 500 feet. The datum should be below the lowest elevations

[2] Raymond A. Hill, *op. cit.*

[3] F. H. Lahee, *Field Geology*, 3d ed. (1931), pp. 457–67. McGraw-Hill Book Company, New York.

to be measured, so that all corrections will have the same sign, but should not be lower than necessary lest the correction figures become too large for convenience.

To each reading of the barometer is applied a temperature correction appropriate to the height of the station above the chosen datum. The amount of the correction is determined from a graph such as Figure 1 on which are plotted curves for various temperatures above and below 50° and for which the coördinates are the difference in elevation and the necessary correction. This method of graphically determining the temperature correction is not different in principle from that used by Lahee, but the writer prefers to let the curves represent actual observed temperature, instead of the difference between the observed temperature and 50°, and to print the ordinate representing difference in elevation along the long side of the graph instead of along the short side, as is done by Lahee.

The actual computations naturally divide themselves into two steps: first, the preparation of the correction curve for the day; and, second, the computation of the elevations of individual stations by the use of this curve.

In the first step—the preparation of the correction curve—the points which fix the curve are determined by *adding* algebraically (the sum to be added being positive if the temperature is above 50° and negative if it is below 50°) to the apparent correction at each bench mark the temperature correction appropriate to the difference in elevation between that bench mark and the datum plane being used. The following example may be used, referring to the data in Table I and the curves (Fig. 2), and using 500 feet as the datum plane

TABLE I

DATA USED IN ILLUSTRATIVE EXAMPLES

Barometer Reading, Feet	*Time*	*Temperature °F.*	*Station*	*Computed Elevation, Feet*
525	9:30 A.M.	70	B.M. 500	x
624	9:45		1	600
750	10:00		2	730
919	11:00		B.M. 900	x
768	12:50 P.M.	86	B.M. 730	x
830	1:00		3	797
834	1:30		B.M. 800	x
640	1:45		4	590
930	2:00	89	5	906
647	4:00	90	Check 1	600
700	4:30		6	660

to which temperature corrections are computed. At B.M.730 at 12:50 P.M., the barometer read 768 and the apparent correction was +38 feet (barometer 38 feet too high). The temperature was 86°.

The temperature correction for 230 feet above datum (730–500) at 86° is +16 feet, approximately (Fig. I); therefore, the desired control point for the curve is +54 feet (+38+16). If the barometer reading had been 680 feet (barometer 50 feet too low), the apparent correction would have been −50 and the control point for the curve would have been −34 feet (−50+16). If the temperature had been 20° instead of 86° and the barometer reading 768, the apparent correction would have been +38, the temperature correction −14 (Fig. I), and the control point for the curve would have been +24 (+38−14).

In the second step—computing the elevations of the stations from the barometer readings and the correction curve—the true elevation of the station is determined by first applying to the observed reading

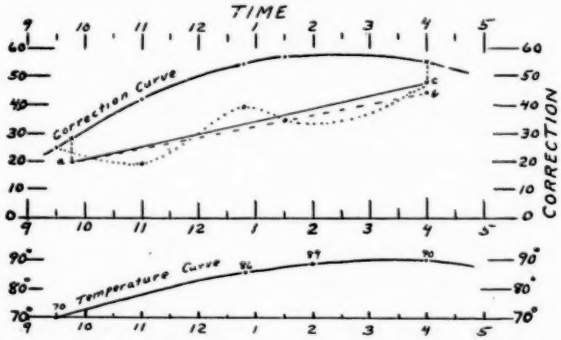


FIG. 2.—Barometer correction and temperature curves for data in Table I, using 500-foot datum. Dotted line shows barometer curve that would have resulted if temperature correction had been neglected.

the correction indicated by the curve, and then adding, algebraically (a negative quantity if the temperature is below 50°), the temperature correction for the difference between the true elevation and the datum. For example, at 9:45 A.M., the barometer read 624 and the temperature was 72°. Referring to the curve (Fig. 2), the apparent correction at 9:45 A.M. is found to be +28 feet. The indicated elevation is, therefore, 596 (624−28). The temperature correction for 96 feet (596−500) above datum at 72° is 4 feet; therefore, the true elevation is 600 feet (596+4).

Attention is called to the fact that the temperature correction as obtained is not strictly accurate in that no account was taken of the fact that the true elevation above datum is not 96 feet but is 96+4, or 100 feet, and that, strictly, the temperature correction for 100 feet instead of that for 96 feet should have been used. In this case, the

discrepancy is a small fraction of a foot and can be neglected, but for high temperatures and high relief it is necessary to avoid this error by determining approximately the amount of the temperature correction as in the example above, adding this to the indicated elevation above datum, and then obtaining the true temperature correction for their sum. For example, at 2:00 P.M. the barometer reading was 930 and the temperature was 89°. Reference to the curve, Figure 2, shows that the apparent correction at 2:00 P.M. is +57 feet. The indicated elevation is 873 (930−57). The temperature correction for 373 feet (873−500) at 89° is 30 feet, therefore the true elevation above datum is not 373, but approximately 30 feet higher than that, and the temperature correction for 403 (373+30) is 33 feet, and the true elevation is 906 feet (873+33).

This additional step is necessary only where the relief is so great and the temperature so far from 50° that the error resulting from neglecting it becomes greater than it is desired to allow. The adjustment is readily made mentally, for in looking up the correction for 373 feet one readily notes that it is approximately 30 feet and therefore uses 373 plus 30 instead of 373.

In the practical application of this method there is no confusion as to procedure if one follows two simple rules (which may advantageously be recorded on the graph of Figure 1). These rules apply to temperatures above 50°. For temperatures below 50°, the temperature correction will, of course, be a negative quantity.

Rule 1. In constructing the correction curve, add (algebraically) to the apparent correction the temperature correction for the elevation of the bench mark above datum.

Rule 2. For determining a station elevation, add to or subtract from the observed reading the correction indicated by the correction curve and then add (algebraically) the temperature correction (a negative quantity if below 50°) for the true elevation above the datum selected.

If the relief is considerable and the temperature far from 50°, it will also be necessary to add (algebraically) the trial temperature correction to the indicated elevation in order to obtain the true temperature correction as already explained.

For the case where the correction curve is constructed partly from the records of repeated readings on a station of unknown elevation, the temperature correction must be taken into account in determining trial points on the curve if the temperature change between readings has been considerable. For example, as shown in Table I, two readings were made on Station 1, the first at 9:45 A.M., when the

temperature was 72°, and another at 4:00 P.M., when the temperature was 90°. The observed difference in the readings was 23 feet (647−624), but in the meantime the temperature had risen 18°. The figure to be used in locating the points on the trial curve would, therefore, not be 23 feet (*ab* of Figure 2), but would be 23 feet plus a temperature correction equal to the difference between the correction for the height of Sta. 1 above datum at 72° and that for the same height at 90°. This may be obtained from the chart (Fig. I) by taking the correction for the elevation of Sta. 1 above datum for a temperature as much above 50° as the difference in temperature of the two readings. But the exact elevation of Sta. 1 above datum is not known when the curve is being constructed. Its approximate elevation can, however, be obtained from the trial curve as already established from known bench marks and will be sufficient for the purpose.

Referring again to Figure 2, it can be readily determined from the curve as platted from known bench marks that the elevation of Sta. 1 is approximately 600 feet.The correction for 100 feet (600−500) at 18° (90−72) above 50° is 4 feet; therefore, the trial point *c* is 27 feet (23+4) above point *a*. The line *ac* can now be drawn and the position of the correction curve at 4:00 P.M. determined in the usual manner. The foregoing calculation can be made easier by the construction of a graph showing the correction for various elevations above datum and various differences in temperature between readings, or it can be made by multiplying the elevation of the station above datum by 0.2 per cent of the difference in temperature between readings.

The method here described may appear, on first reading, to be rather complicated, but in practice it is not, because, where the relief is moderate, the trial temperature correction can readily be made mentally, and in many cases need not be used, and it is only in exceptional cases that the difference in temperature between repeat readings on a station of unknown elevation is great enough to require the temperature correction in locating the trial points for the construction of the correction curve.

By using a good modern instrument and making the necessary temperature corrections, surprisingly accurate work can be done with a barometer, provided reasonable care is taken to avoid unfavorable weather conditions.

JOHN L. RICH

CINCINNATI, OHIO

FORMULAS FOR CALCULATING STRATIGRAPHIC THICKNESS EXPOSED BETWEEN TWO DIPS

Recently in the examination of one of our thick California formations it was found necessary to determine accurately the thickness exposed between various outcrop samples collected for microfaunal determination. Planetable traverses were run connecting the different exposures, and these traverses were of a zig-zag shape inclined generally to the strike of the formation. In order to calculate the thickness between the different exposures, special formulas had to be worked out. I am giving here the simplest of these formulas, believing they may be useful to others encountering the same field conditions.

Given two exposures on, say, a hillside, showing dips and strikes that may correspond, or may be quite different: it is required to find the stratigraphic thickness measured normal to the bedding exposed between the two dips. The strata between are concealed, and the assumption is made that the dip as well as the strike varies in a uniform manner from the first to the second outcrop. The straight line, rarely level, connecting the two dips is denoted by s. The relations are shown in Figure A.

The coördinates of the two exposures are $(x_1y_1z_1)$ and $(x_2y_2z_2)$. The positive x axis is directed north, the positive y axis east, and the positive z axis vertically upward. These coördinates provide for the horizontal positions of the dips, as well as their elevations.

The direction cosines (L, M, N) of the line s are given on Figure A. Here $s^2=(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2$.

The direction cosines (l, m, n) of the normal to the bedding plane at any point on the line s are given on Figure B expressed in terms of the dip and strike, and also in terms of the intercepts. If we make the assumption that the direction cosines vary in a linear manner between the two dips, then these quantities are determinable in the concealed strata at any point along the line s.

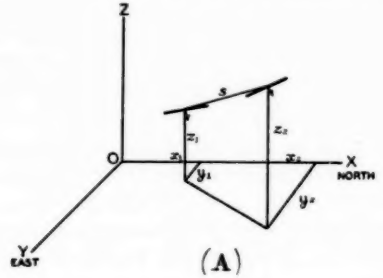
The direction cosines of the normal to the bedding plane at the first exposure are $(l_1m_1n_1)$ and at the second exposure $(l_2m_2n_2)$.

Let dT be the normal to the bedding plane at any point on the line s. Also dT represents the elementary stratigraphic thickness at this point. The angle ϵ between the normal dT and the line s is found from the equation: $\cos\epsilon=Ll+Mm+Nn$. It is further evident that dT is the projection of ds, hence $dT=ds\cos\epsilon$.

Therefore $dT=(Ll+Mm+Nn)ds$.

Integrating this on the assumption that (l, m, n) are linear between the two exposures, we get the stratigraphic thickness T exposed between the two outcrops to be:

$$T=\tfrac{1}{2}s(L(l_1+l_2)+M(m_1+m_2)+N(n_1+n_2)) \qquad (1)$$



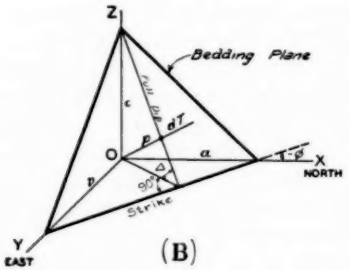
Direction Cosines of Line s :-

$L = \frac{x_2 - x_1}{S}$

$M = \frac{y_2 - y_1}{S}$

$N = \frac{z_2 - z_1}{S}$

(A)



(B)

ϕ = Strike of bedding plane.

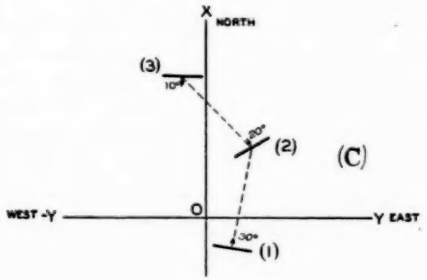
Δ = Dip of bedding plane.

Direction Cosines of Normal to bedding plane (p or dT) :-

$l = \sin\phi . \sin\Delta = P/a$

$m = -\cos\phi . \sin\Delta = P/b$

$n = \cos\Delta = P/c$



This can be reduced to the more simple and usable form:

$$T=\tfrac{1}{2}((x_2-x_1)(l_1+l_2)+(y_2-y_1)(m_1+m_2)+(z_2-z_1)(n_1+n_2)) \qquad (2)$$

In these equations the direction cosines are expressed in terms of the dip and strike as follows:

$$l_1 = \sin\phi_1 \sin\Delta_1 \qquad l_2 = \sin\phi_2 \sin\Delta_2$$
$$m_1 = -\cos\phi_1 \sin\Delta_1 \qquad m_2 = -\cos\phi_2 \sin\Delta_2$$
$$n_1 = \cos\Delta_1 \qquad n_2 = \cos\Delta_2 \qquad (3)$$

where Δ_1 is the dip and ϕ_1 is the strike at the first exposure, and Δ_2 is the dip and ϕ_2 is the srtike at the second exposure.

That is, equation 1 or 2 taken with 3 is sufficient to determine the stratigraphic thickness between the two outcrops.

In using these equations strict attention must be given to the sign of the quantities. Table I shows the signs of the different elements for various directions of dip and strike.

In Table I (l, m, n) are the direction cosines of the normal to the bedding plane at any point on line s; ϕ is the strike of the bedding plane, measured from a north-south line; Δ is the dip of the bedding plane measured from the horizontal. Both the dip and strike are expressed as acute angles. The signs given below obviously apply to the two exposures at the extremities of the line s.

TABLE I

TABLE OF SIGNS

Strike angle ϕ	*Strike*	l	m	n	*Direction of Dip*	*Dip* Δ
+	NE.–SW.	+	−	+	NW.	+
+	NE.–SW.	−	+	+	SE.	−
−	NW.–SE.	−	−	+	SW.	+
−	NW.–SE.	+	+	+	NE.	−
0°	N.–S.	0	−	+	W.	+
0°	N.–S.	0	+	+	E.	−
90°	E.–W.	+	0	+	N.	+
90°	E.–W.	−	0	+	S.	−
+	NE.–SW.	+	−	0	Vertical	90°
−	NW.–SE.	−	−	0	Vertical	90°
90°	E.–W.	1	0	0	Vertical	90°
0°	N.–S.	0	1	0	Vertical	90°
No strike	—	0	0	1	Horizontal	0°

By means of the foregoing formulas the stratigraphic thickness of a large section can be computed by means of dips arranged in a zig-zag fashion across the outcrop of the formation. The calculations are easy, but the signs must be watched. Positive values of T indicate that the second exposure is stratigraphically above the first. Negative values of T indicate that the second exposure is stratigraphically below the first.

The scattered dips can also be projected perpendicularly on one straight traverse line and the thicknesses determined graphically. The projected dip or component of dip along the straight traverse line selected can be found from the equation

$$\tan\Delta' = \cos\rho \cdot \tan\Delta$$

where ρ = angle beteeen the traverse line and direction of full dip at any exposure

Δ = full dip of the exposure

Δ' = component of dip to be used along the traverse line for the graphical determinations.

EXAMPLE

In the following example the dips are situated as shown in Figure C. The origin of the coördinate system is put at any convenient point on the map; in the present case the origin is at sea-level so that the z coördinates represent the elevations of the exposures. The coördinates of each outcrop are measured from the origin. The method shown in Table II can be used for the calculations.

TABLE II

Exp.	*Strike*	ϕ	*Dip*	Δ	*Feet*			l	m	n
					x	y	z			
1	N.80°W.	−80°	30°NE.	−30°	− 39	+30	+210	+.493	+.087	+.866
2	N.60°E.	+60°	20°NW.	+20°	+ 82	+52	+190	+.296	−.171	+.940
3	E.-W.	90°	10°S.	−10°	+168	−30	+240	−.174	0	+.985

The direction cosines are found thus:

For 1: $l = \sin(-80)\sin(-30) = (-.985)(-.500) = +.493$

$m = -\cos(-80)\sin(-30) = -(.174)(-.500) = +.087$

$n = \cos(-30) = +.866$. And likewise for the rest.

For the thickness between 1 and 2 use equation: $x_2 - x_1 = 82(-39) = 121$; $y_2 - y_1 = 52 - 30 = 22$; $z_2 - z_1 = 190 - 210 = -20$; $l_1 + l_2 = .493 + .296 = .789$; $m_1 + m_2 = .087 - .171 = -.084$; $n_1 + n_2 = .866 + .940 = 1.806$. Hence the thickness, $T = \frac{1}{2}(121(.789) - 22(.084) - 20(1.806)) = 28.8$ feet.

For the thickness exposed between 2 and 3 we have: $x_2 - x_1 = 168 - 82 = 86$; $y_2 - y_1 = -30 - 52 = -82$; $z_2 - z_1 = 240 - 190 = 50$; $l_1 + l_2 = .296 - .174 = .122$; $m_1 + m_2 = -.171 + 0 = -.171$; $n_1 + n_2 = .940 + .985 = 1.925$. Hence the thickness, $T = \frac{1}{2}(86(.122) + 82(.171) + 50(1.925)) = 60.4$ feet.

These results are checked within a few feet by those obtained by the method of projecting the dips on one straight traverse line and determining the thicknesses graphically, using parallel or concentric folding.

E. L. Ickes

10463 Tennessee Ave.
West Los Angeles, California
November 27, 1933

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 143-148, 2 FIGS.

DISCUSSION

EVOLUTION OF PETROLEUM

DISCUSSION OF W. F. SEYER'S "CONVERSION OF FATTY AND WAXY SUBSTANCES INTO PETROLEUM HYDROCARBONS"[1]

The conditions of laboratory experimentation never completely duplicate the conditions of natural geologic processes. If the results of the laboratory experimentation, whether geological or chemical, do not show at least a fair degree of correlation with the geologic features with which they are supposed to correspond, the laboratory conditions and processes have failed somehow to duplicate the natural conditions and processes; and without further analysis, the results of the laboratory experimentation, and the theory which is built upon them, should not be applied to the explanation of those geologic features.

The chemical theory of the youthfulness of the paraffine hydrocarbons and the matureness of the naphthenic hydrocarbons, which is advocated by Professor Seyer and which appeals to a great many, but not all, chemists who have studied the transformation of petroleum, however, is directly contrary to the strong weight of geologic evidence.

The thesis which Professor Seyer advocates briefly is as follows.

A. Protopetroleum is paraffinic.

B. Under the effect of heat and with the passage of time, there is a tendency for

> an accumulation of light gaseous hydrocarbons with a high hydrogen-carbon ratio on the one hand, and on the other, liquid and solid hydrocarbons becoming ever poorer in hydrogen. Dense saturated molecules with low hydrogen-carbon ratios such as the polycyclic naphthenes are produced to greater and greater extent.

C. On account of the rate of decomposition, the mother substance of petroleum must have been exposed to a temperature of 200°C. for petroleum to have formed within the limits of geologic time.

D. If *A*, *B*, and *C*, for example, represent respectively the youthful, mature, and old age stages in the life history of a petroleum, or respectively oils of young, middle, and old geologic ages, the base of *A* should be paraffinic, of *B* mixed paraffinic and asphaltic, and of *C* asphaltic.

He discusses the effect of time, but not the effect of depth; but he says,

> So far as is known, the rate of primary decomposition is a function of temperature, although investigation in the future may show that the great pressures found in oil beds also exert an influence, and if so, will probably be found to increase the rate of decomposition.

Temperature increases with depth, although somewhat slowly; and pressure increases rapidly with depth. It would seem a legitimate extension of Professor Seyer's theory to postulate that the alteration which he sees taking place with time, should also take place with increasing depth.

[1] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 10 (October, 1933), pp. 1251–67.

The character-age relation: naphthene-base oils in formations of relatively young geologic age, and of paraffine-base oils in the relatively old formations, holds throughout the world. The Tertiary oils characteristically are naphthenic; and naphthenic oils characteristically are of Tertiary age. Paleozoic oils characteristically are paraffinic; and paraffinic oils characteristically are of Paleozoic and Mesozoic age.

A statistical study of the variation of the character of petroleum with age in the United States is given in Figure 1. As ready criteria for the character of the base of a crude, the United States Bureau of Mines uses the gravity of the 250°–275° cut under atmospheric pressure, and the cloud test of the 200°–225° cut under 40 mm. pressure. The United States Bureau of Mines has established that the A. P. I. gravity of the 250°–275° key cut will be 40°

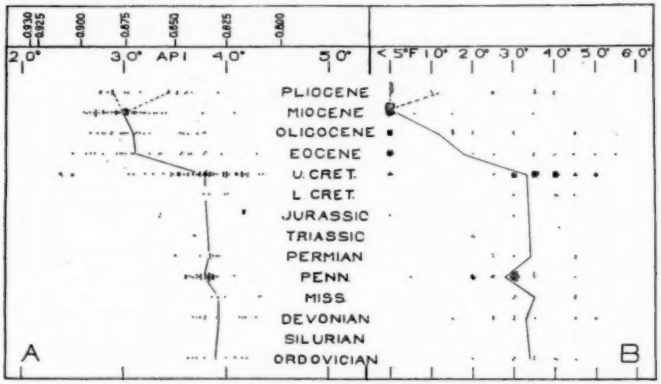


FIG. 1

or more, if the base is paraffinic; 30°–37.9° if the base is intermediate; less than 30° if the base is hybrid or naphthenic; and that wax is present and the base is hybrid, if the cloud test of the 200°–225°C. cut is 5°F. or above. The gravity and the cloud point respectively for those key cuts have been plotted in Figure 1, for all published and some unpublished United States Bureau of Mines analyses for which the writer has the geologic age of the oil sand from which the sample came.

The A. P. I. gravity of the first key cut shows a definite increase at the rate of approximately 2.25° per geologic period for the Tertiary and Cretaceous crude oils but no change or only very slight increase for oils of Cretaceous to Ordovician age. The cloud test for the second key fraction correspondingly shows an increase through the Tertiary and Cretaceous and only slight irregularity from the Cretaceous to Ordovician. The Pliocene oils fall into two groups: a group whose first key cut has an A. P. I. gravity of 29°± and a second group whose first key cut has an A. P. I. gravity greater than 34°. The second group comprises California crude oils, which come from oil fields having enormous depth ranges. The gravity of the first key cut and the cloud test for the second key cut for the first group of Pliocene oils lie approximately on the line of variation for the Miocene-Cretaceous oils.

Three *a priori* explanations of the major trend of the character-age variation in Figure 1 seem possible.

1. The present character of the oil depends wholly on the organic mother source material, which changed from geologic period to geologic period.

2. Chemically, the mother source material was the same for all the oils; the present character of the crude oil depends on transformation of the crude oil progressively with time. The transformation is in the direction: from naphthenic through hybrid, almost through intermediate to paraffinic. The change, however, seems to be asymptotic to an oil which just misses being paraffinic according to the United States Bureau of Mines' definition.

3. There may have been a change in the character of the source material with the passage of geologic periods, but the progressive transformation of the character of the oil may also have taken place.

There is certainly no evidence that the more primitive petroleums are paraffinic; further, if the three ages, *A*, *B*, and *C*, are taken similarly as in Professor Seyer's supposition (p. 1266), the base of the average crude oil of each age will be respectively, naphthenic, intermediate toward naphthenic, intermediate toward paraffinic, or in the looser parlance of more ordinary usage, asphalt base, mixed base, and paraffine base. That order is the reverse of that which Professor Seyer postulates for the age variation of petroleum.

Transformation of crude oil of a given age from naphthene base to paraffine base under the effect of depth-linked factors seems definitely to be shown by the Eocene crude oils of the Texas-Louisiana Gulf Coast. The A. P. I. gravity of the first key cut and the cloud test for the second key cut are plotted in Figure 2 against present depth of the oil sand for 21 United States Bureau of Mines analyses. A strikingly high degree of correlation was shown between the present depth and the A. P. I. gravity of the first key cut. The Pearson product correlation coefficient is 0.75 ± 0.06 for an increase of the gravity of that cut from 26.4° A. P. I. at 500 feet, at the rate of 2.15° A. P. I. to a gravity of 38.4° at a depth of 6,000 feet; and theoretically to a gravity of 40° A. P. I. at a depth of 6,800 feet. The cloud test of the second key cut shows a corresponding correlation with depth. All the samples from depths less than 3,250 feet had a cloud test of less than 5°F., and all the samples but one from depths greater than 3,350 had a cloud test greater than 20°F. It should be noticed also that the A. P. I. gravity of the first key cut of the younger Eocene oils (Jackson) is consistently less than the average; and, excepting for two crude oils, that A. P. I. gravity for the older Eocene oils (Claiborne and Wilcox) is greater than the average.

That depth variation of the Eocene crude oils must mark the transformation of crude oil under the effect of temperature and pressure. Decrease of the A. P. I. gravity of crude oil has been explained rather commonly and glibly in the past as the result of the greater evaporation of the lighter constituents from the shallower crude oils. That explanation is not applicable to this variation of the two key cuts, for each cut represents so narrow a fraction of the crude oil, that for practical purposes it may be regarded as a single constituent. The observed variation must mark a variation of the molecular make-up of that constituent. Those samples of Figure 2 came from many different oil fields in the Gulf Coast. The only known and surmised consistent variation in the conditions which affected the crudes from which those samples came is the depth of the respective oil sands. The two factors which pre-

sumably may affect the character of the crude oil and which vary with depth are temperature and pressure. If temperature and pressure under the limits of available geologic time can produce change in the character of crude oil, seemingly within the narrow range of temperatures and within the greater but not excessive range of pressures which affect the oil sands, the rate of change should increase with increase of depth and the shallower crude oil should be nearer, and the deeper crude oils should be farther, from the character of the primitive crude oil. The observed variation of the Eocene crude oil of the Gulf Coast, therefore, indicates that the primitive Eocene crude oil was naphthenic or a yet more complex petroleum. The higher A. P. I.

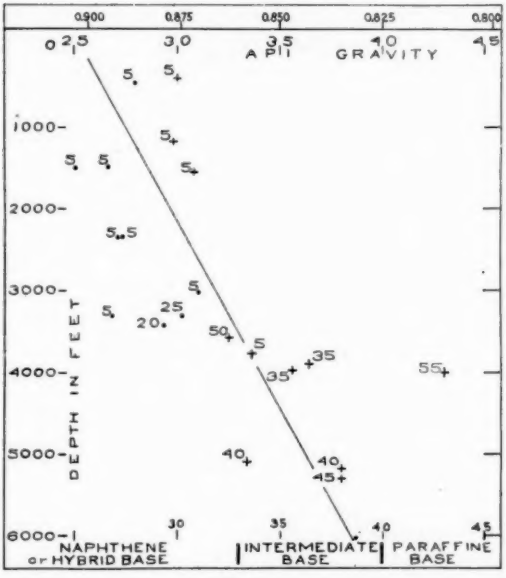


FIG. 2

gravity of the first key cut of the older compared with the younger Eocene oils, *a priori* might be the effect of original differences in the character of the mother source material, but equally well it may be the time effect of those factors which are transforming the crude oil. It is in the same direction as the general variation from period to period within the Tertiary plus the Cretaceous. It adds weight, therefore, to the evidence that the protopetroleum is naphthenic or yet more complex and that the evolution of crude oil is from the naphthenic series toward and not away from the paraffine series.

The temperatures at which the formation of petroleum starts must be far below the temperature of 200°C. which is postulated by Professor Seyer; at least for Gulf Coast crude oil. The geologic history of the Gulf Coast is relatively simple. It is quite impossible that the Gulf Coast crude oils which are now being produced, have been subjected to temperature as high as 100°C.

Some of the crude oil from the deeper sands may have been subjected to temperatures as high as, but not much higher than 70°C. Much of the crude oil can not have been subjected to temperatures much higher than 50°C. The normal depth which the oil sands would have had without uplift is known. The character of the oil varies with age and depth so that we know that the normal, average crude oil is indigenous to the formation in which it is found and that it has not migrated up from greater depth. The temperatures which now prevail in the subsurface within reach of the drill are known. The observed evolution of the Gulf Coast crude oil must have taken place at temperatures far below 100°C. and geologically temperatures of 200°C. must not be postulated in connection with the formation of Gulf Coast crude.

Dissent must also be expressed by the writer to Heald's statement that geologists would agree that the end product of petroleum will be gas and solid hydrocarbons. The writer's detailed study of the natural history of petroleum has still far to go. But the results to date suggest that gas and the lighter members of the paraffine hydrocarbons are the normal end products in the evolution of petroleum. It is, of course, true that under special conditions, solid hydrocarbons may form as end products, but the normal trend seems to be in the direction of lighter and more paraffinic oils.

The areas in which the carbon ratio is above the critical point seem to the writer to be areas in which the evolution of petroleum has been greatly accelerated toward its end stage by the abnormal heat and pressure. Petroleum in such areas consists of gas and the lightest liquid fractions. Those solid petroleums should be detected in drilling, if they are present in the quantity which is postulated by Professor Seyer, but solid petroleums are a curiosity in drilling; they do not seem to occur with the abundance that would be required under the theory that the end points in the normal evolution of crude oil are gas and solid petroleum.

In connection with the question of the evolution of petroleum, reference should also be made to the writer's paper, "Natural History of Petroleum with Special Reference to the Gulf Coast Crude Oil,"[2] and to Wallace E. Pratt's paper, "Hydrogenation and the Origin of Oil."[2] The writer's paper reports the results of a study of the variation of the composition of the Gulf Coast crude oil in terms of the gasoline, kerosene, gas oil lubricating fractions, "carbon," sulphur, and A. P. I. gravity. The character of the normal Gulf Coast crude oil and the normal East Texas and Rocky Mountain Cretaceous crude oil may be represented as a three-dimensional block diagram in which the three dimensions are: character, geologic age, and present depth of the producing sand. The shallower and younger crude oils tend to be composed predominantly of gas oil and of the yet heavier fractions. The older and deeper crude oils are composed predominantly of gas oil and of the yet lighter fractions. The transformation which the writer observed involves progressive enrichment of the hydrogen content of the crude oil. Wallace Pratt, with the aid of his colleagues, the physical chemists of the Humble Oil and Refining Company, explains this hydrogen enrichment of the crude oil as the result of methanation of the oil. Methane is present in contact with, and is dissolved in, the Gulf Coast crude oil. Pratt, with the advice of his physical chemists, postulates chemical reaction between the methane and the crude oil and the

[2] *Problems of Petroleum Geology, A Sequel to Structure of Typical American Oil Fields* (Amer. Assoc. Petrol. Geol., 1934, in press).

absorption of the carbon and hydrogen atoms of the methane into the molecules of the crude oil. Pratt does not go far in explanation of the origin of the methane, but observes that it is found in considerable quantity in association with the Gulf Coast crude oil. An explanation of the methane which is advocated by the writer is as follows.

A. Methane forms easily from the decomposition of many types of organic material.

B. Petroleum may form only from a limited range of organic material.

C. Both types of material may be commingled in the mother source beds of petroleum; methane and petroleum might form more or less simultaneously, the former from the wide range of organic material; the latter from its limited range of mother organic source material.

The methane and petroleum, of course, might form in adjacent beds.

DONALD C. BARTON

HOUSTON, TEXAS
December 2, 1933

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 149-153

REVIEWS AND NEW PUBLICATIONS

Angewandte Geophysic für Bergleute und Geologen, I Teil (Practical Geophysics for Engineers and Geologists, Part 1). By HERMANN REICH. Akad. Verlagsgesell. m. b. H. (Leipzig, 1933). 151 pp., 74 figs. 6¼×9¼ inches. Paper. Price, 12.60 R. M.

The purpose of this book is the explanation in non-mathematical terms of the principles of practical geophysics and their application to geological problems.

The first part of the book discusses the physical properties of the earth with special reference to density, elasticity, magnetic susceptibility, and electrical conductivity.

This is followed by a description of the instruments and methods used in determining subsurface structure through the measurements of variations in the aforementioned constants.

The final chapters treat the application of geophysical methods to specific geologic problems.

More emphasis is given to the torsion balance and seismograph refraction method than to the other methods and the discussions of these methods are adequate. The treatment of the reflection method is extremely sketchy and also inaccurate, mainly because developments of the last three or four years are not included. The spread from shot point to recording position is given as 1.2 to 1.8 times the depth of the reflecting bed. No discussion is given of the method as applied to particular geological problems.

The electrical method likewise is given a very brief treatment.

L. Y. FAUST
Geophysical Research
Corporation

TULSA, OKLAHOMA
November 15, 1933

"Oil and Gas Fields of Michigan." By ROBERT B. NEWCOMBE. *Michigan Dept. of Conserv. Geol. Survey Div. Pub. 38, Geol. Ser. 32.* Lansing, Michigan (1933). 293 pp., 10 pls., 16 text figs., 25 insert figs. Price: cloth, $2.50; paper, $2.00.

That a "discussion of the depositional and structural features of the Michigan Basin" may be so written that it is acceptable as a dissertation for the degree of Doctor of Philosophy (University of Michigan) and at the same time be acceptable as a State report to be read by the layman is proved by the latest publication issued by the Michigan Geological Survey: "Oil and Gas Fields of Michigan," by Robert B. Newcombe.

The report, Dr. Newcombe ingenuously states, "consists of a consolidation of *all the known geological data* (the reviewer's italics) into a regional study with particular emphasis on depositional and structural features." The documentation shows the wide and catholic scope of reading preparatory to

writing the report and the report itself shows the care with which Dr. Newcombe winnowed the literature and garnered every grain of fact that might solve the problems of the unique conditions of the Michigan Basin.

The geological record of the "Basin," so long and almost completely hidden by a thick mantle of glacial drift, is gradually being revealed by deep drilling in the Southern Peninsula of Michigan. Since 1925 the records of more than 1,600 wells have made available geological data heretofore concealed and, with this information and data, and facts secured from studies by others, of the structural provinces surrounding the area, the author advances an ingenious and quite plausible hypothesis of the origin and development of the "Basin" which is a noteworthy contribution to the literature of geology.

Newcombe states the "Basin" has some of the features of a geosyncline and also features of a major structural basin. He relates the origin of the Michigan syncline to the Keweenawan disturbance, to movements from the northeast acting against the positive Wisconsin land mass—analogous to the formation of the Appalachian geosyncline of a later date; and contends the later development and evolution into an oval basin (not the circular dish-shaped basin of earlier geologists) to be related to those movements which produced the east branch of the Cincinnati arch and culminated in the Appalachian revolution.

Detailed discussions of the geography of the state (Chap. II), of the descriptive, historical, and structural geology (Chaps. III, IV, V) which lead to this conclusion, with a clear discussion of the hypothesis (Chap. VI) are included in Part I of the report. The arguments are pointed and clarified by a wealth of figures, cross sections, and areal, structural, contour, and isopach maps. Sources of error, incompleteness of data, and objections which may be brought by paleontologists, stratigraphers, and others, to historical and structural interpretations and conclusions are recognized and the hypothesis stated as a basis for future study as new facts accumulate.

Part II of the report is a discussion of the economic geology of the oil and gas fields of the state. It contains detailed discussion of the structures of the almost abandoned Muskegon pool, of the active Central Michigan fields, of the undrilled Howell fault area, their geology, water conditions, oil and gas developments, and future prospects. A long chapter on the known, undeveloped structures (in 54 counties) completes the report.

Inasmuch as the earlier publications, 14 and 37, of the Survey on oil and gas, are now out of print, geologists, as well as the oil fraternity, would have appreciated a similar detailed discussion of the Port Huron, Deerfield, and Saginaw structures. Because they are detailed in the earlier publications, they are dismissed with brief descriptions. Also, if one must criticize, a chapter on drilling methods might have been added for the benefit of the layman, as this is a State report.

R. A. Smith, State Geologist, should be commended for fostering this report. He has done both the State of Michigan and the geological profession a service in publishing this Doctor's dissertation as a State document.

HELEN M. MARTIN

905 WEST ALLEGAN STREET
LANSING, MICHIGAN
December 5, 1933

Igneous Rocks and the Depths of the Earth. By REGINALD ALDWORTH DALY. McGraw-Hill Book Company, New York (1933). 598 pp., 193 illus. Price $5.00.

This book is by no means a textbook of petrology in a narrow sense, since it gives no descriptions of the igneous rocks. It is rather a treatise on our present knowledge of the more theoretical phases of vulcanism, such as the origin and structure of the earth, and the production and differentiation of magmas, and the application of studies on these subjects to a genetic classification of igneous rocks. The book is stated by the author to be a practically complete rewriting of *Igneous Rocks and Their Origin* (1914) in the light of recent advances in knowledge of the igneous rocks themselves and of geochemistry and geophysics. Certain hypotheses introduced in *Our Mobile Earth* (1926) are also incorporated in the work.

Chapter I gives a brief abstract of the book. Part I, Chapters II–VIII, is entitled "Leading Facts" and treats of types of igneous rocks, their distribution and relative quantities, eruptive types and geological time, physical properties of rocks, injected bodies, subjacent bodies, and extrusive bodies. This part presents the factual groundwork for the more theoretical portion of the book which follows.

Part II, Chapters IX–XV, has the heading "A General Theory." It includes the subjects: outer shells of the earth; internal heat of the earth; abyssal injection; magmatic stoping; pure melting and assimilation of rocks, and abyssoliths; differentiation of magmas; and mechanism of volcanic vents of the central type. Some of the theses and conclusions of these chapters are the following.

1. The distinction between the dominantly acid rocks (Sial) of the plateau-like continents and the dominantly basic rocks (Sima) underlying the ocean basins and the continents at depth.

2. That the rocks to some such average depth as 80 kilometers are crystalline and constitute a veritable "earth's crust."

3. That below that depth lie successively more dense, rigid but weak shells of basic rock, which is vitreous because the temperature is too high for crystallization to take place, surrounding a specially dense central core.

4. That most magmas originate in the outermost of these vitreous shells, near its contact with the outer crystalline shell; that basaltic magmas come from the vitreous shell; and granitic magmas, at least in large part, from blocks of the "crust" foundered in the vitreous shell during the process of "continental slide."

5. That primitive heat (from a formerly molten earth) has been at least as important as radioactivity in establishing the thermal gradient at the surface of the globe and in furnishing the heat that through the ages has been dissipated into space.

6. That Sial and Sima became separated from a primitive basic magma by repeated crystal fractionation, aided by gaseous transfer and perhaps by liquid unmixing.

7. That magmatic stoping and abyssal melting of pure rocks are even more important than they were considered to be in the author's earlier work.

Part III, Chapters XVI–XXII, treats of the different rock clans and suggests a genetic classification for them. The order of consideration is gabbro

clan, granite clan, diorite clan, granodiorite clan, syenite clan, feldspathoidal clans, ultramafic rocks, magmatic ores, and carbonatites. The general theory developed in Part II is applied to the origin of each group in turn. Chapter XXIII, "Principles and Projects," points out the problems of petrogenesis and the fields in which observation and research are particularly desirable. The author closes the book with these words:

> Now and for long years to come petrologists will be occupied with these complex riddles. If the present book adds stimulus toward such researches, its purpose shall have been largely accomplished. There is a "world of work" to be done!

The reviewer does not pretend to be capable of discussing this book critically, but he has found it very interesting and stimulating.

L. C. SNIDER

NEW YORK, N. Y.
December 6, 1933

RECENT PUBLICATIONS

ALASKA

"Progress of Surveys in the Anthracite Ridge District, Alaska," by R. W. Richards and G. W. Waring. *U. S. Geol. Survey Bull. 849-A* (1933). Coal is of semi-anthracite rank, but exploration thus far is inadequate to prove presence of workable deposits. Supt. of Documents, Govt. Printing Office, Washington, D. C. Price, $0.05.

ALGERIA

"The Diatomaceous and Fish-Bearing Beida Stage of Algeria," by Robert Van Vleck Anderson. *Jour. Geol.*, Vol. 41, No. 7 (October-November, 1933). Pp. 673–98, 4 figs.

CALIFORNIA

"Bibliography of the Geology and Mineral Deposits of California, to December 31, 1930," by Solon Shedd. *California State Div. Mines Bull. 104* (1933). 400+ pp. Complete list of publications on geology, mines, oil, coal, mineral deposits, fossils, earthquakes, rock formations, et cetera, of California. Contains chapter on "Pioneers of the Geology of California," by F. M. Anderson; 20 pictures. Division of Mines, Ferry Bldg., San Francisco. Price, prepaid, $2.15.

GENERAL

"Guidebook of the Western United States, The Southern Pacific Lines, New Orleans to Los Angeles," by N. H. Darton. *U. S. Geol. Survey Bull. 845* (1933). The sixth in the popular series of guidebooks to the geology of the United States along the western railroads. Supt. of Documents, Govt. Printing Office, Washington, D. C. Price, $1.00.

"The Bleaching Clays," by P. G. Nutting. *U. S. Geol. Survey Cir. 3* (1933). Paper includes data from study of 200 clays. Free on application to the director of the U. S. Geol. Survey, Washington, D. C.

"Sand-Petrographie und ihre ölgeologische Bedeutung" (Sand-Petrography and its Importance in Petroleum Geology), by Hans Runge. *Inter. Zeit. Bohrtec. Erdölb., und Geol.* (Vienna), Vol. 41, No. 22 (November, 1933), pp. 251–58; 3 charts. From *Mitteilung. a. d. Erdölforschungsinstitut der Bergakademie Clausthal.* Summary in English.

GEOPHYSICS

"Physics of the Earth—VI. Seismology," by the Subsidiary Committee on Seismology, Division of Physical Sciences, with the coöperation of the Division of Geology and Geography, and the American Geophysical Union. *Natl. Research Council Bull. 90* (Washington, D. C., October, 1933). 223 pp., 28 figs. Approx. 7×10 inches. Price: paper, $2.00; cloth, $2.50.

ILLINOIS

Publications of the Geology, Mineral Resources, and Mineral Industries of Illinois, with Appended Index (September 1, 1933). Illinois State Geol. Survey (Urbana). 83 pp.

INDIA

"Anthracolithic Faunas of the Southern Shan States," by F. R. Cowper Reed. *Records Geol. Survey India* (Delhi), Vol. 67, Pt. 1 (April, 1933), pp. 1–82; 2 pls. Permo-Carboniferous (?) fossils from black limestones.

"Stratigraphic Significance of the Fusulinids of the Lower Productus Limestone of the Salt Range," by Carl O. Dunbar. *Records Geol. Survey India*, Vol. 66, Pt. 4 (June, 1933), pp. 405–13. Eurasian Permian.

IOWA

"The Red Oak-Stennett-Lewis Traverso of Iowa," by G. E. Condra and J. E. Upp. *Nebraska Geol. Survey Paper 3* (Lincoln, 1933). 23 pp., 4 figs. Study of Pennsylvanian beds exposed in Nishnabotna Valley in Iowa.

KANSAS

"Development of the Oil and Gas Resources of Kansas in 1928 and 1929," by Anthony Folger; "1932," by Roy H. Hall; *Kansas Geol. Survey Min. Resources Cir. 2* (1933). 174 pp., 3 figs. Much valuable information, especially of western Kansas. University of Kansas, Lawrence. Price, $0.20.

"Preliminary Report on Ground Water Resources of the Shallow Water Basin in Scott and Finney Counties, Kansas," by Rycroft G. Moss. 7 pp., 3 figs. Price, $0.15.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 154-156

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

E. G. Leonardon, Paris, France
C. Schlumberger, P. Charrin, Paul L. Vaudoit

Jeanette Elizabeth Wendel, Chicago, Ill.
Fred M. Bullard, R. B. Newcombe, Theron Wasson

FOR ASSOCIATE MEMBERSHIP

Charles Hurst Sample, Houston, Tex.
Phil F. Martyn, C. A. Warner, Don E. Mathes

Edgar Smith Sherar, Palembang, Sumatra, D. E. I.
Dave P. Carlton, Wallace E. Pratt, L. P. Teas

FOR TRANSFER TO ACTIVE MEMBERSHIP

Charles Ivan Alexander, Shreveport, La.
W. M. Winton, Gayle Scott, F. B. Plummer

NINETEENTH ANNUAL MEETING, DALLAS, MARCH 22-24

The nineteenth annual meeting of the Association will be held at Dallas, Texas, March 22, 23, and 24, at the invitation of the Dallas Petroleum Geologists. The Baker Hotel has been selected as convention headquarters. The Adolphus Hotel is just across the street. The Dallas geologists have selected Clyde M. Bennett, vice-president and assistant manager of the Magnolia Petroleum Company, as chairman of the general committee.

Dallas is conveniently situated for the majority of petroleum geologists and the Baker Hotel is well prepared to handle a large and enthusiastic convention. More detailed announcement of the plans and program will be mailed to Association members.

The members of the general committee are as follows.

Clyde M. Bennett, chairman; R. S. McFarland, vice-chairman; L. J. Pepperberg, W. E. Wrather, Leon F. Russ, C. A. Hammill, R. T. Hill, J. W. Bostick, Ellis Shuler, and the following sub-committee chairmen.

Technical program.—F. H. Lahee.
Finance.—R. B. Whitehead.
Entertainment.—Joseph M. Wilson.
Exhibits and equipment.—George E. Dorsey.
Reservation and registration.—F. E. Heath.
Publicity.—S. M. Aronson.
Golf.—Edwin B. Hopkins.
Trips.—Alfred Gray.
Reception and ladies.—L. W. Orynski.

Titles and abstracts of manuscripts (1) for the general program should be sent without delay to F. H. Lahee, Box 2880, Dallas, Texas; (2) for the geophysics program, to L. W. Blau, Humble Oil and Refining Company, Houston, Texas.

It is desirable that manuscripts be submitted before February 15, and certainly before March 1, so that the whole program may be satisfactorily arranged. The program committee plans to select for oral presentation those papers which seem to be of most general interest. The authors of these papers will be allowed sufficient time for reading and other members will be allowed adequate time for discussion. It is desirable to have the usual, large number of papers submitted for listing on the program and for consideration for *Bulletin* publication, but it is the plan to reduce the number of papers actually presented possibly to four in each half-day session. It is hoped that the committee will have the coöperation of members in all parts of the country in submitting papers and in being willing to let the committee select the papers for oral presentation.

The following subjects have been submitted.

"Geological Aspects of Well Spacing," by M. G. Cheney

"Geological Exhibit at A Century of Progress," by Theodore A. Link

"Conroe and Tom Ball Oil Fields, Texas," by L. P. Teas and F. W. Michaux

"Fault Systems of Gulf Coastal Plain," by Ed. W. Owen

"Hilbig Serpentine Oil Field, Bastrop County, Texas," by W. C. Blackburn.

ASSOCIATION COMMITTEES

EXECUTIVE COMMITTEE

FRANK R. CLARK, *chairman*, Mid-Kansas Oil and Gas Company, Tulsa, Oklahoma
WILLIAM B. HEROY, *secretary*, Consolidated Oil Corporation, New York, N. Y.
FREDERIC H. LAHEE, Sun Oil Company, Dallas, Texas
GEORGE SAWTELLE, Kirby Petroleum Company, Houston, Texas
L. C. SNIDER, H. L. Doherty and Company, New York, N. Y.

GENERAL BUSINESS COMMITTEE

RUSSEL S. KNAPPEN (1934), *chairman*, Gypsy Oil Company, Box 661, Tulsa, Oklahoma
ED. W. ORVEN (1934), *vice-chairman*, 1015 Milam Building, San Antonio, Texas

ARTHUR A. BAKER (1934)
ALBERT L. BEEKLY (1934)
FRANK R. CLARK (1935)
H. E. CRUM (1935)
JOSEPH A. DAWSON (1935)
C. E. DOBBIN (1935)
JAMES TERRY DUCE (1935)
WALTER A. ENGLISH (1934)
H. B. FUQUA (1935)
M. W. GRIMM (1935)
S. A. GROGAN (1935)
WILLIAM B. HEROY (1934)
JOHN F. HOSTERMAN (1935)
EDGAR KRAUS (1935)
FREDERIC H. LAHEE (1934)
ROLAND W. LAUGHLIN (1935)
THEODORE A. LINK (1935)
R. T. LYONS (1935)
ROY G. MEAD (1935)
A. F. MORRIS (1935)
WILLIAM M. NICHOLLS (1934)
PHILIP E. NOLAN (1935)
L. W. ORYNSKI (1934)
CLARENCE F. OSBORNE (1935)
E. E. ROSAIRE (1934)
GEORGE SAWTELLE (1934)
L. C. SNIDER (1934)
J. D. THOMPSON (1934)
WALLACE C. THOMPSON (1935)
PAUL WEAVER (1935)
G. H. WESTBY (1934)
E. A. WYMAN (1935)

RESEARCH COMMITTEE

DONALD C. BARTON (1936), *chairman*, Petroleum Building, Houston, Texas
M. G. CHENEY (1934), *vice-chairman*, Coleman, Texas

K. C HEALD (1934)
F. H. LAHEE (1934)
H. A. LEY (1934)
R. C. MOORE (1934)
F. B. PLUMMER (1934)
C. E. DOBBIN (1935)
A. I. LEVORSEN (1935)
ALEX. W. MCCOY (1935)
C. V. MILLIKAN (1935)
L. C. SNIDER (1935)
L. C. UREN (1935)
HAROLD W. HOOTS (1936)
R. S. KNAPPEN (1936)
W. C. SPOONER (1936)
PARKER D. TRASK (1936)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY NATIONAL RESEARCH COUNCIL

R. S. KNAPPEN (1934)

GEOLOGIC NAMES AND CORRELATIONS COMMITTEE

M. G. CHENEY, *chairman*, Coleman, Texas

JOHN G. BARTRAM
IRA H. CRAM
ALEXANDER DEUSSEN
B. F. HAKE
G. D. HANNA
A. I. LEVORSEN
C. L. MOODY
R. C. MOORE
ED. W. OWEN

TRUSTEES OF REVOLVING PUBLICATION FUND

E. DEGOLYER (1934) FRANK R. CLARK (1935) CHARLES H. ROW (1936)

TRUSTEES OF RESEARCH FUND

W. E. WRATHER (1934) ALEX. W. MCCOY (1935) ROBERT H. DOTT (1936)

FINANCE COMMITTEE

E. DEGOLYER (1934) W. E. WRATHER (1935) JOSEPH E. POGUE (1936)

COMMITTEE ON APPLICATIONS OF GEOLOGY

F. H. LAHEE, *chairman*, Box 2880, Dallas, Texas

WILLIAM H. ATKINSON
DONALD C. BARTON
FORD BRADISH
ARTHUR E. BRAINERD
H. A. BUEHLER
HAL P. BYBEE
W. F. CHISHOLM
HERSCHEL H. COOPER
CAREY CRONEIS
MARVIN LEE
S. E. SLIPPER
E. K. SOPER
LUTHER H. WHITE
R. B. WHITEHEAD

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 1 (JANUARY, 1934), PP. 157-160

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

W. E. HEATER, formerly of Ritzville, Washington, is now with the Nederlandsche Pacific Petroleum Maatschappij, Batavia, Java, Dutch East Indies.

The Dallas Petroleum Geologists elected the following officers November 24: chairman, F. E. HEATH, Sun Oil Company; vice-chairman, J. C. KARCHER, Geophysical Service, Inc.; secretary-treasurer, CHARLES B. CARPENTER, petroleum engineer with the U. S. Bureau of Mines.

FRANK B. NOTESTEIN, formerly of Box 295, Wooster, Ohio, is now with The Texas Company, Houston, Texas.

HAROLD M. HORTON, geologist with the Superior Oil Company of California, has changed his address from Dallas to 504 Esperson Building, Houston, Texas.

E. J. BOOS, formerly of Wichita, Kansas, may be addressed at Phillips Petroleum Company, Box 355, Saginaw, Michigan.

HOWARD F. NASH, formerly of Polson, Montana, is now located at Apartado 234, Maracaibo, Venezuela, S. A.

CARL W. HUBMAN has changed his address from Box 15, Boulder, Colorado, to C/de Ultramar S. A. P. A., 778 Calle Chile, Buenos Aires, Argentina.

WILLIAM NORVAL BALLARD, geologist with the Phillips Petroleum Company, has been transferred from Bartlesville, Oklahoma, to Saginaw, Michigan.

Mrs. MARGARET FULLER BOOS, who is completing a 3-year study of the heavy minerals of the granites of the Front Range of Colorado and Wyoming, presented a paper on this subject before the Geological Society of America at Chicago, in December. The work has been assisted by grants in 1932 and 1933 from the National Research Council. C. MAYNARD BOOS is now employed as geophysicist by the Phillips Petroleum Company. Mr. and Mrs. Boos have returned to their home, 424 South Seneca Street, Bartlesville, Oklahoma.

GEORGE R. PINKLEY, formerly of San Antonio, Texas, is now employed as field geologist for the Creole Petroleum Company, Caripito, Venezuela. He sailed from New York on December 9 for South America.

WILLIAM J. MILLARD has resigned from the firm of Huntley and Huntley, of Pittsburgh, Pennsylvania, and is doing independent consulting work in South America and the United States. His present address is 4224 Hastings Street, El Paso, Texas.

SAM H. HOUSTON, JR., and Miss EDITH LOUISE PURDY were married on December 5 at Lake Providence, Louisiana. Houston is with the Humble Oil and Refining Company, at Lake Charles, Louisiana.

CHARLES E. DECKER addressed the Tulsa Geological Society, on December 4, on "Viola Limestone, Primarily of Arbuckle and Wichita Mountain Region."

GEORGE W. PIRTLE, member of the firm of Hudnall and Pirtle, Consulting Geologists, of Tyler, Texas, delivered a paper before the Shreveport Geological Society at their regular meeting on December 1, on "Geology of the Michigan Basin."

E. H. TOLLEFSON has changed his address from 2 Sherman Street, Wellsboro, Pennsylvania, to Hope Construction and Refining Company, Clarksburg, West Virginia.

MAYNARD H. STEIG, formerly of the Houston Oil Company of Texas, at Houston, is now with the Shell Petroleum Corporation, 1118 South Texas Bank Building, San Antonio, Texas.

A. J. BAUERNSCHMIDT, JR., has resigned as geologist for the Union Sulphur Company at Sulphur, Louisiana, and has accepted a position as district geologist and paleontologist for the Magnolia Petroleum Company, with headquarters in the Weber Building at Lake Charles, Louisiana. His address is Box 872.

MELBERT SCHWARZ, formerly of Bryan, Texas, is now associated with the Texas Seaboard Oil Company, Dallas, Texas, as a petroleum engineer.

DELMER L. POWERS, geologist with the Continental Oil Company, has been transferred from Denver, Colorado, to Billings, Montana.

JAMES W. HUNTER, formerly with the Huasteca Petroleum Company, in Mexico, has been transferred to the Standard Oil Company of Venezuela, Caripito, Venezuela, via Port of Spain.

J. B. WHISENANT has moved from Laredo, Texas, to 206 East Lullwood, San Antonio, where he has opened offices with JOHN TRENCHARD.

A. W. WEEKS has changed his address from 1118 City National Bank Building, San Antonio, Texas, to the Shell Petroleum Corporation, Exploration Department, Houston, Texas.

E. B. STILES, formerly geologist for The Pure Oil Company, at Fort Worth, is now located at Palestine, Texas, as resident paleontologist for the Tide Water Oil Company and Texas Seaboard Oil Company for the Long Lake field.

IONEL I. GARDESCU, of the petroleum engineering department of the A. and M. College of Texas, has been retained by The Texas Company in a consulting capacity.

J. H. VAN ZANT, chief geologist of the Eason Oil Company, and manager of the Grisso Royalty Company, both of Enid, Oklahoma, and Miss RUTH CHAMPLIN were married early in December, at Enid.

R. J. METCALF, geologist for the Mid-Kansas Oil and Gas Company, formerly at Fort Worth, is now with the same company at 1418 Milam Building, San Antonio, Texas, where the company recently moved the district headquarters for Texas, Louisiana, and New Mexico.

W. C. RAUCH, geologist with the Superior Oil Company, at Houston, Texas, was injured in an automobile accident near Lafayette, Louisiana, on December 8. He is at present confined at St. John Hospital, at Layafette, where he expects to be for some months.

G. A. WARING is in New Mexico and Arizona for two or three months in charge of the United States Geological Survey's investigation of the groundwater supply in the High Plateau region. Engaged with him on this investigation are D. A. ANDREWS, E. B. ECKEL, M. M. KNECHTEL, and M. A. HARRELL.

The Oklahoma City Geological Society has elected the following officers for the year 1934: president, HAROLD S. THOMAS, T. B. Slick Estates; vice-president, EDWARD I. THOMPSON, Phillips Petroleum Company; secretary-treasurer, R. W. BRAUCHLI, Anderson-Prichard Oil Corporation.

W. TAPPOLET, geologist for the Royal Dutch Shell Group in Mexico, is on a three months leave in Switzerland. He may be addressed at Raemistrasse 56, Zurich 7, Switzerland.

O. F. SUNDT, formerly with the Gulf Production Company, recently opened an office as consulting geophysicist at 1615 Sterling Building, Houston, Texas, and will specialize on gravity work on the Gulf Coast.

At a luncheon meeting of the North Texas Geological Society, on December 15, the chief discussion centered on what geological work might be suggested to the Administration of Public Works as most valuable for that area. President Ralph Powell presided.

The West Texas Geological Society elected the following officers at their annual meeting held December 14 at San Angelo: president, CAREY P. BUTCHER, Cardinal Oil Company, San Angelo; vice-president, MORGAN E. ROBERTS, Pure Oil Company, Odessa; secretary-treasurer, W. C. KINKLE, Mid-Kansas Oil and Gas Company, San Angelo.

The Kansas Geological Society elected the following officers at their annual meeting held recently: president, E. C. MONCRIEF, Derby Oil Company; vice-president, R. A. WHORTON, Producers and Refiners Corporation; secretary-treasurer, HOWARD L. BRYANT, Skelly Oil Company. New directors include LARRY HAY, consulting geologist, Wichita; PHIL K. COCHRAN, Carter Oil Company; and E. L. BRADLEY, consulting geologist.

A. I. LEVORSEN, research geologist for Phillips Petroleum Company at Bartlesville, was principal speaker before the December meeting of the Kansas Geological Society. Levorsen spoke on Paleontology.

The address of WALTER E. HOPPER, consulting geologist, is Box 1280, Shreveport, Louisiana.

EARLE R. WALL, of the California Company, presented a discussion "Stratigraphy of Starr County and Southern Zapata County, Texas," before the San Antonio Geological Society, December 4.

J. E. UPP, of the Conservation and Survey Division of the University of Nebraska at Lincoln, has a Government appointment to study the Pierre shale in connection with a problem along Missouri River and a short distance up Cheyenne, Bad, and White rivers.

WILLIAM L. RUSSELL, 430 Temple Street, New Haven, Connecticut, was working temporarily for oil operators in Kentucky, last month.

The eighth International Petroleum Exposition and Congress, Tulsa, Oklahoma, will be held on May 12–19, 1934, on its own 20-acre site. W. G. SKELLY is president and WILLIAM B. WAY is general manager. W. A. SCHLUETER is chairman of the scientific and technical committee.

The International Congress of Geography will be held in Warsaw, August 23–31, 1934. The address is 6 Rakowiecka Str., High School of Commerce, Warsaw, Poland.

W. C. SPOONER, consulting geologist of Shreveport, Louisiana, spent part of the fall in Mexico.

S. P. BORDEN maintains a consulting geological office at 721 Slattery Building, Shreveport, Louisiana.

ROBERT ROTH gave a paper "Evidences of Triassic in Kansas, Oklahoma, and Texas," before the Tulsa Geological Society, December 18.

L. P. TEAS, of the Humble Oil and Refining Company, Houston, Texas, presented a paper on Developments in the "Conroe trend" before the Shreveport Geological Society, January 5.

The annual meeting of the American Institute of Mining and Metallurgical Engineers will be held on February 19–22 in New York City.

GEORGE H. BARTON, father of DONALD C. BARTON, recently died at the age of 81 years. Since 1902 he was director of the Teachers School of Science, conducted under the auspices of the extension department of Harvard University.

JOHN JOLY, professor of geology and mineralogy at the University of Dublin, died on December 8, at the age of 76 years.